Industrial Materials for the Future (IMF) R&D Priorities

RICHARD SILBERGLITT • JONATHAN MITCHELL

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PREFACE

This documented briefing summarizes the results of an independent review of the vision statements, technical roadmaps, and other documents relevant to the Industries of the Future strategy, an initiative of the U.S. Department of Energy's (DOE's) Office of Industrial Technologies (OIT).

These are the initial results of a study RAND is conducting in support of the OIT Industrial Materials for the Future (IMF) program. The study's objective is to identify and prioritize industrial materials research needed to meet Industries of the Future objectives. The study will provide data and analysis that will support an advanced materials research and development (R&D) portfolio to meet the future needs of OIT and the nine Industries of the Future.

The study is being performed under the auspices of RAND Science and Technology and is being conducted for the National Renewable Energy Laboratory (NREL). Inquiries regarding RAND Science and Technology may be directed to the addresses below.

Stephen Rattien
Director
RAND Science and Technology

RAND
1200 South Hayes Street
Arlington, VA 22202-5050

Phone: (703) 413-1100 x5219
Web: www.rand.org/scitech/

SUMMARY

The Office of Industrial Technologies (OIT), part of the DOE's Office of Energy Efficiency and Renewable Energy, develops and delivers advanced energy efficiency, renewable energy, and pollution prevention technologies for U.S. industrial applications. OIT's strategy for achieving these goals is called Industries of the Future. Key to this strategy are partnerships with industry, in the form of a series of teams consisting of representatives of the nine energy-intensive industries on which OIT is focusing its R&D portfolio. Each of the teams—aluminum, glass, steel, metal casting, petroleum, mining, forest products, agriculture-bioproducts, and chemicals—has developed its own vision statement and technology roadmap.[1] These documents encapsulate the technology performance targets the teams believe will increase energy efficiency and productivity and reduce environmental impact.

The Industrial Materials for the Future (IMF) program was formed in FY 2000 and incorporates two OIT programs: Advanced Industrial Materials (AIM) and Continuous Fiber Ceramic Composites (CFCC). IMF provides data and analysis supporting an advanced materials R&D portfolio to meet the future needs of OIT and the Industries of the Future. Specifically, IMF's mission is to research, design, develop, engineer, and test new and improved materials, as well as more profitable uses of existing materials.[2] The IMF program plan notes that the OIT industry teams address short-term materials needs for specific industries. IMF does not support materials technologies of sufficient maturity to compete for such team funding. Rather, IMF focuses on the longer-range needs of industry by sponsoring R&D that requires nurturing to mature enough to compete for OIT industry team funding.

IMF emphasizes materials needs common to multiple Industries of the Future. The IMF program's strategy is to identify and support promising technologies to the point that they can be demonstrated in industrial applications. Accordingly, approximately one-third of IMF funding is dedicated to core research that underpins these research areas. The program focuses on filling the gaps between the basic research that the DOE Office of Science conducts and the nearer-term applied R&D projects that the OIT industry teams sponsor. Finally, IMF is seeking to develop classes of materials with suites of properties beyond the capabilities of existing commercial materials.

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[1]The vision statements and technical roadmaps are available at http://www.oit.doe.gov.

[2]DOE, Office of Energy Efficiency and Renewable Energy, Office of Industrial Technologies, *Program Plan for Fiscal Years 2000 Through 2004, Industrial Materials for the Future (IMF)*, July 2000, p. i.

RAND conducted an independent review to identify materials research needs that both (1) arise from the goals and objectives of OIT's Industries of the Future strategy, as delineated in the vision statements and technical roadmaps, and (2) are consistent with the mission of the IMF program. To create a basis for this identification, RAND developed a series of matrices, one for each of the nine OIT industries, that present these research needs. These matrices are on the enclosed compact disc, as an Excel file.

This documented briefing explains the procedures RAND used to construct the performance target–research priority matrices and to identify the high-priority materials research needs that are consistent with IMF's mission. The enclosed compact disc also provides a color version of the briefing slides, as a Portable Document Format (PDF) file, to better illustrate the matrices, as well as a PDF of this documented briefing.

PERFORMANCE TARGET–RESEARCH PRIORITY MATRICES

There is a performance target–research priority matrix for each of the nine OIT industries. The rows present the performance targets from the Industries of the Future technology roadmaps. Each grouping of three columns represents a high-priority materials R&D need from either the industry roadmaps or a recent National Materials Advisory Board (NMAB) review of the materials needs of these industries.[3] The individual columns indicate specific numbers of projects that address each need that each of three groups—DOE's Office of Science, the IMF program, and the OIT industry teams (vision teams[4])—is currently sponsoring.[5]

After constructing the matrices, RAND's next step was to identify materials R&D activities that both have high priority for the OIT industries (that is, they address the materials R&D needs in the matrices) and that are consistent with the IMF mission. This dictated emphasizing less-mature technologies and research that could potentially provide combinations of properties not found in existing commercial materials. RAND ruled out areas in which the industry teams are already sponsoring research, unless there was a clear need for additional core research or for multiple-industry research to provide new materials technology options for future industry team efforts. Table S.1 presents the resulting list of high-priority materials R&D for the nine Industries of the Future. The

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[3]NMAB, *Materials Technologies for the Process Industries of the Future: Management Strategies and Research Opportunities*, NMAB-496, National Academy Press, 2000.

[4]*Vision team* (VT) is an older term for the OIT industry teams; the abbreviation is used in the matrices and is therefore retained in the slides.

[5]Data for the matrices came from *Energy Materials Coordinating Committee (EMaCC) Annual Technical Report, Fiscal Year 1999*, DOE/SC-0025, October 31, 2000; *Materials Sciences Programs, Fiscal Year 1997*, DOE/SC-0001, October 1998; OIT Web site.

Table S.1

High-Priority Materials R&D

Industry	Needed Materials Research
Aluminum	High-temperature materials, including refractories Casting Advanced forming Tool and die materials Databases and modeling Joining and welding *Materials for highly caustic environments* *Rolling and extrusion* *Products and microstructure processing*
Glass	High-temperature materials database Robust nonrefractory materials Hot glass contact materials Improved refractories Improved heat-recovery materials Coatings *Multiple sensor needs* *Glass melting and forming models* *Surface and interface properties* *Use of microwaves and ultrasonic means of controlling glass shape*
Steel	Wear-resistant materials High-temperature materials and refractories Coating properties, processing, and applications Tooling Joining Process modeling *Refractory repair (for cokemaking)* *Energy-saving processes*
Metal casting	Computer design tools Mold and die fill modeling Casting (properties, microstructure, and processing) Dies and coatings Refractories Reduced emissions Joining of new alloys *Testing standards* *Waste-stream treatment, recycling, and use*
Chemicals	Ceramic and composite reliability and performance data High-temperature materials, including refractories Erosion- and corrosion-resistant materials and coatings Materials for separations

Table S.1—Continued

Industry	Needed Materials Research
	Joining, including oxide dispersion strengthened superalloys
	Thermophysical, kinetic, mechanical materials data
	Stress-corrosion cracking of construction materials
	Nondestructive evaluation (NDE) for fracture toughness
	Surface chemistry modeling
	Composition-corrosion relationships for carbon steel
Petroleum	Membranes
	Catalysts
	Combustion and yield modeling
	Fouling-resistant materials and coatings
	Computational catalyst design
	NDE and inspection
	Corrosion monitoring
	In situ residual stress measurement
Forest products	Separation technologies
	High-temperature materials, including refractories
	Erosion- and corrosion-resistant materials
	Welding
	Databases and modeling
	Environmentally conscious treatments
	Drying and pressing
	Sensor materials
	Adhesives
	Waste and by-product treatment, extraction, and use
Agriculture	Separation technologies
	Materials for harvesting equipment
	Materials for new reactors/fermentation
	Materials for biocatalysis
	Standards and product quality
Mining	Wear-resistant materials
	Physical separation
	Process modeling and simulation
	Mineral characterization
	Membrane systems
	By-product characterization, recycling, and use

areas that IMF is addressing as of this writing appear in plain type; those the program is not currently addressing are in italics.

MULTIPLE-INDUSTRY RESEARCH PRIORITIES

Several IMF R&D priorities that emerged from the review of the matrices apply to more than one of the nine industries and thus form the basis for a research portfolio consistent with the IMF mission. Table S.2 presents these multiple-industry research priorities, together with the industries to which each applies. The first six priorities apply to a majority of five or more of the Industries of the Future; the remaining five apply to no more than four of them.

Figure S.1 shows how the IMF multiple-industry research priorities in Table S.2 meet the requirements of from three to all nine industries. Of the eight multiple-industry research

Table S.2

IMF Multiple-Industry Research Priorities

Priority	Industries
Corrosion-, erosion-, and wear-resistant materials	Aluminum, glass, steel, metal casting, chemicals, petroleum, forest products, agriculture, mining
Databases and modeling	Aluminum, glass, steel, metal casting, chemicals, petroleum, forest products, mining
High-temperature materials and refractories	Aluminum, glass, steel, metal casting, chemicals, forest products
Membranes and physical separation	Chemicals, petroleum, forest products, agriculture, mining
Joining and welding	Aluminum, steel, metal casting, chemicals, forest products
Coatings	Glass, steel, metal casting , chemicals, petroleum, forest products
Waste and by-product treatment, recycling, and use	Metal casting, forest products, mining
Casting (microstructure and processing)	Aluminum, steel, metal casting
Tools and dies	Aluminum, steel, metal casting
Sensor materials	Glass, forest products
Standards, product quality, and testing	Metal casting, agriculture

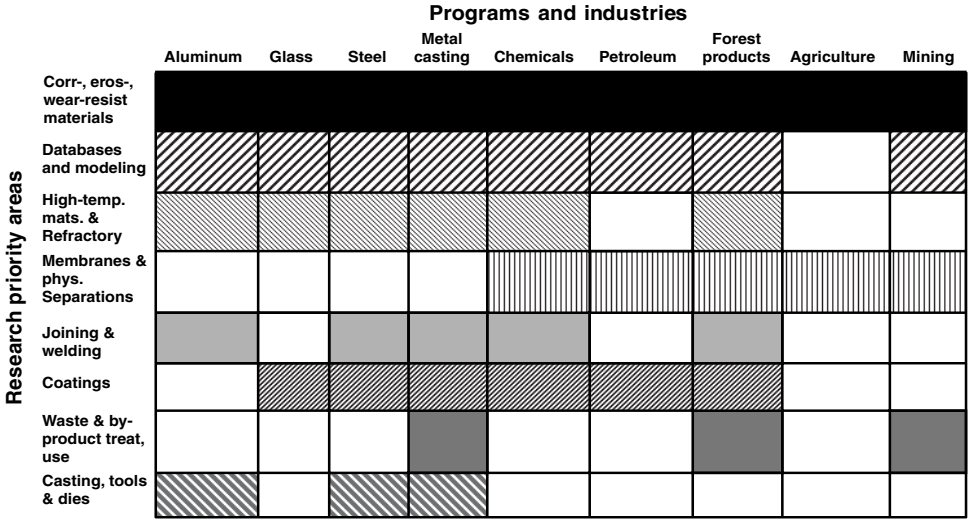


Figure S.1—IMF Multiple-Industry R&D Priorities

priorities, anywhere from two to seven can apply to any one industry. Sensor materials and standards, product quality, and testing each applied to only two of the industries, and thus are not shown.

CORE RESEARCH

Each IMF multiple-industry research area requires underpinning core research. For example, developing erosion- and corrosion-resistant high-temperature materials requires research on high-temperature properties and erosion-corrosion resistance and may well also require database development, if new regimes or suites of properties are being sought. The recent development and application of high-temperature intermetallic alloys to heat-treating fixtures, steel transfer rolls, burner tubes for chemicals and petroleum processing, and forging dies is instructive. Achieving a suite of properties useful for these applications required new compositions *and* new processing methods to develop alloys that were castable, weldable, and corrosion resistant.

Similarly, pursuing the multiple-industry research areas shown in Figure S.1 will require IMF to explore the following core research areas:

- database development
- high-temperature properties
- wear, erosion, and corrosion resistance
- processing and properties relationships

- modeling of processing, forming, and deposition
- separation methods
- materials for sensors
- materials chemistry
- surfaces, interfaces, and joining.

The research in these core areas will provide the opportunities to develop new materials and processing technologies to achieve the Industries of the Future performance targets that depend upon materials research. Each core research area underpins one or more of the multiple-industry R&D areas.

Three crosscutting OIT programs provide research that supports multiple Industries of the Future: IMF, Combustion, and Sensors and Controls. In addition, to support the Industries of the Future, OIT sponsors programs in three supporting industries: heat treating, forging, and welding and joining. Table S.3 presents the multiple crosscutting programs and supporting industry research priorities, together with the programs and industries to which each applies. RAND based this list on its review of the existing program plans, vision statements, and technology roadmaps of the crosscutting OIT programs and supporting industries and on its identification of the materials R&D priorities that are consistent with the IMF mission. The enclosed compact disc also includes a matrix supporting this analysis. While the R&D categories are the same as those for the Industries of the Future, the research areas have a different relative importance for the crosscutting programs and supporting industries. For example, two

Table S.3

IMF Multiple Crosscutting Programs and Supporting Industry Research Priorities

Priority	Industries
Databases and modeling	Heat treating, forging, welding, sensors, combustion
Sensor materials	Heat treating, forging, welding, sensors, combustion
Standards, product quality, and testing	Heat treating, forging, welding, sensors, combustion
High-temperature materials and refractories	Heat treating, welding, sensors, combustion
Waste and by-product treatment, recycling, and use	Heat treating, sensors, combustion
Corrosion-, erosion-, and wear-resistant materials	Forging, welding, sensors
Membranes and physical separation	Sensors, combustion

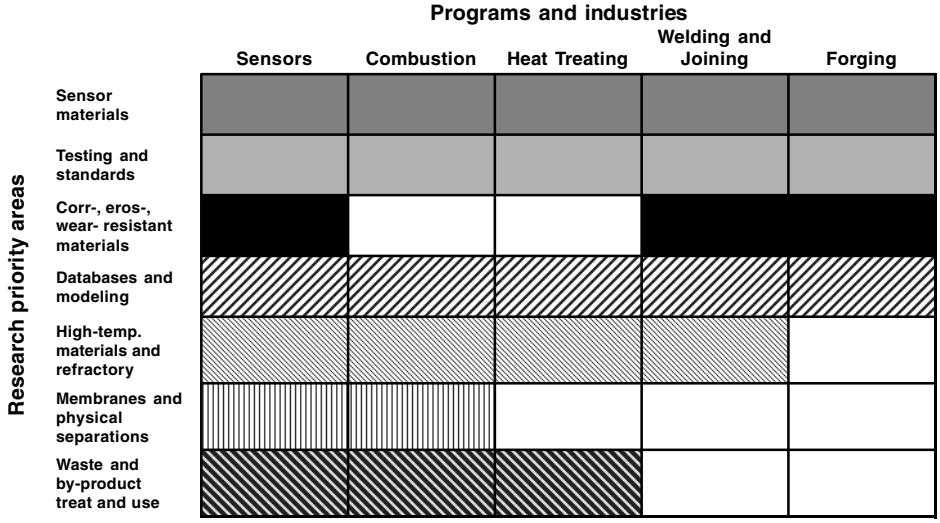


Figure S.2—IMF Multiple Crosscutting Programs and Supporting Industry R&D Priorities

research areas—(1) sensor materials and (2) standards, product quality, and testing—each applied to only two of the OIT industries but applied to all five of the crosscutting programs and supporting industries.

Figure S.2 shows how the research priorities in Table S.3 meet the requirements of from two to all five of the crosscutting programs and supporting industries. Of the seven multiple-industry research priorities, four to seven apply to any one program or industry. The figure does not show (1) joining and welding, (2) coatings, and (3) casting and tools and dies because no more than one crosscutting program or supporting industry identified these as priorities.

NEXT STEPS

RAND will continue work on this project by describing materials performance goals for the multiple-industry R&D areas that emerged from the analysis of this documented briefing. The next step after that will be to describe the technical challenges—which in many cases will require core research efforts—as well as the benefits, of achieving these performance goals.

The final step in the project will be to prioritize the IMF research activities, emphasizing those that fill the gaps between the basic research efforts of DOE's Office of Science and other organizations and the industry-specific research efforts of the OIT industry teams.

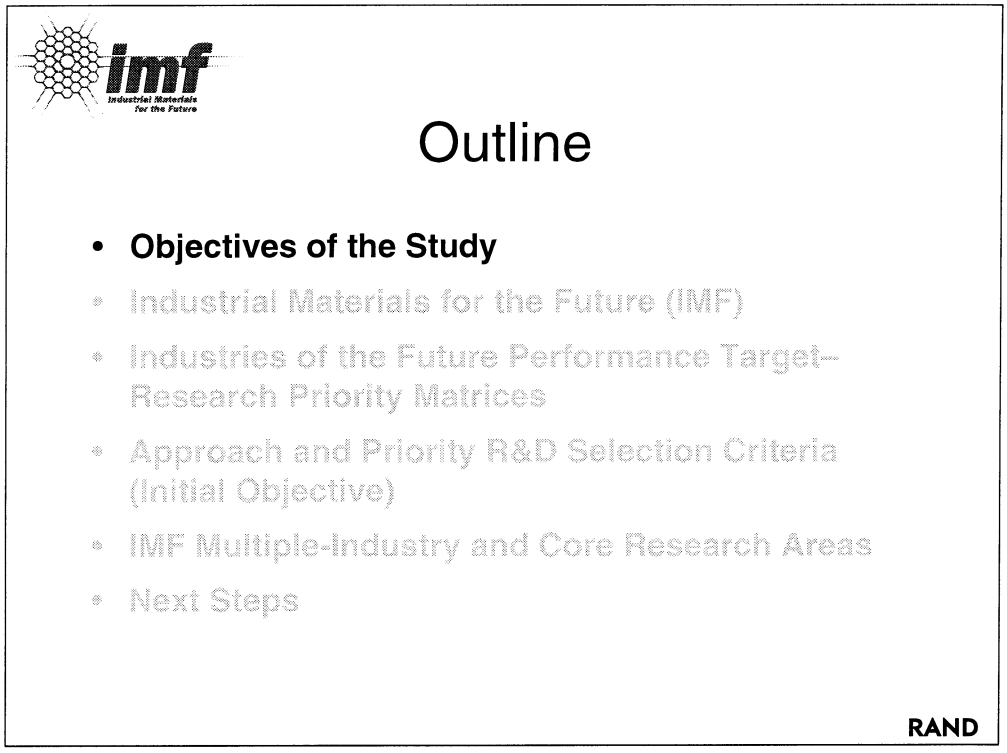
ACKNOWLEDGMENTS

The authors express their appreciation to Lance Sherry of RAND and to Charles Sorrell and Mike Soboroff of the Department of Energy for a number of enlightening discussions and many helpful suggestions during the performance of this work.

Several members of RAND Publications contributed to the final product. Stephen Bloodsworth created the IMF logo, and Sandra Petitijean converted the slides into a form suitable for printing. Phyllis Gilmore edited the text and did the layout, and Christina Pitcher proofread the result. Finally, Christopher Kelly managed the production details, under the direction of Paul Murphy.

ABBREVIATIONS

AIM	Advanced Industrial Materials
CFCC	Continuous Fiber Ceramic Composites
DOE	Department of Energy
EMaCC	Energy Materials Coordinating Committee
FY	Fiscal year
IMF	Industrial Materials for the Future
NDE	Nondestructive evaluation
NMAB	National Materials Advisory Board
OIT	Office of Industrial Technologies
OS	Office of Science
R&D	Research and Development
SBIR	Small Business Innovation Research
VT	Vision team



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[1]The vision statements and technical roadmaps are available at http://www.oit.doe.gov.

and improved materials, as well as more profitable uses of existing materials.[2] The IMF program plan notes that the OIT industry teams address short-term materials needs for specific industries. IMF does not support materials technologies of sufficient maturity to compete for such team funding. Rather, IMF focuses on the longer-range needs of industry by sponsoring R&D that requires nurturing to mature enough to compete for OIT industry team funding.

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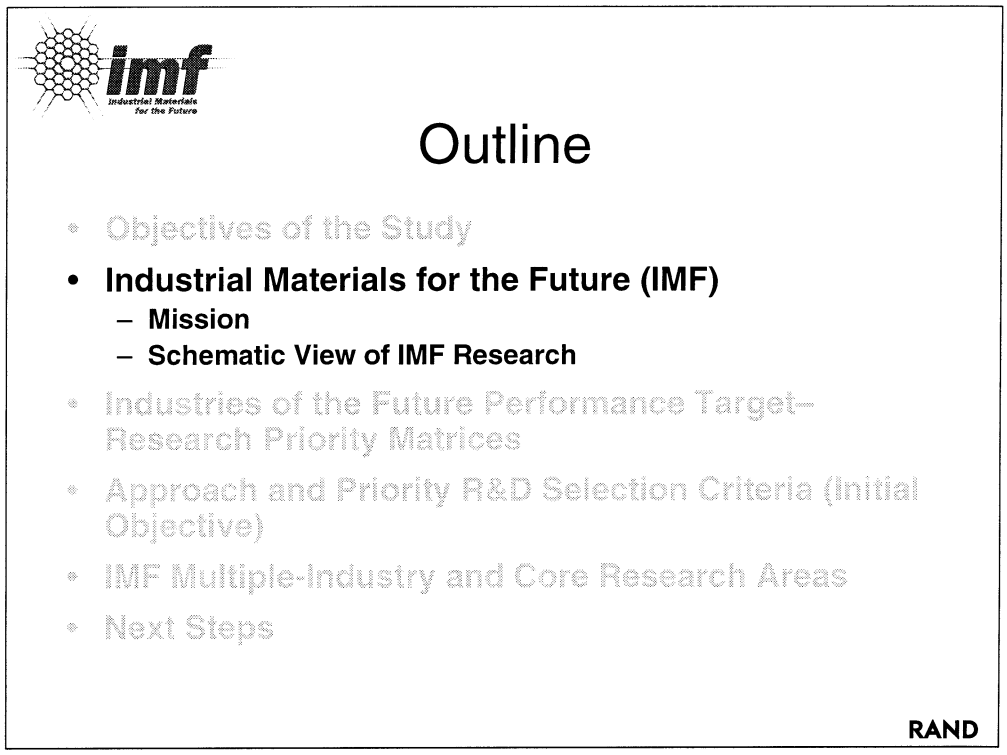
[2]DOE, Office of Energy Efficiency and Renewable Energy, OIT, *Program Plan for Fiscal Years 2000 Through 2004, Industrial Materials for the Future (IMF)*, July 2000, p. i.

The initial objective of the study was to identify the materials research needs that stem from the Industries of the Future goals and objectives delineated in the vision statements and technical roadmaps and that are consistent with the mission of the IMF program. This will provide the basis for an evaluation of the materials performance goals required to achieve the OIT industries' goals and objectives and the associated challenges and benefits. The final objective of the study is to prioritize potential IMF R&D activities.



The following slides set the context for the study by reviewing the mission and role of IMF in sponsoring research that will fill the gaps between basic research that advances scientific knowledge and near-term R&D on mature technologies that can compete for funding from the OIT industry teams.

The IMF program's mission is to research, design, develop, engineer, and test new and improved materials, as well as more profitable uses of existing materials.[1]

The IMF program plan notes that the OIT industry teams address short-term materials needs for specific industries. Thus, IMF will not support materials technologies that are mature enough to compete for such funding. The program instead focuses on longer-range needs of industry, sponsoring R&D that requires nurturing to reach the stage at which it can successfully compete for OIT industry team funding.

The program emphasizes materials needs common to multiple OIT industries. Its strategy is to identify, support, and nurture promising technologies to the point that they can be demonstrated in industrial applications. Accordingly, approximately one-third of IMF's funding is dedicated to core research that underpins these research areas. IMF focuses on filling the gaps between the basic research that the DOE Office of Science conducts and the near-term applied R&D projects that the OIT industry teams sponsor. IMF is seeking to develop classes of materials with suites of properties beyond the capabilities of existing commercial materials.

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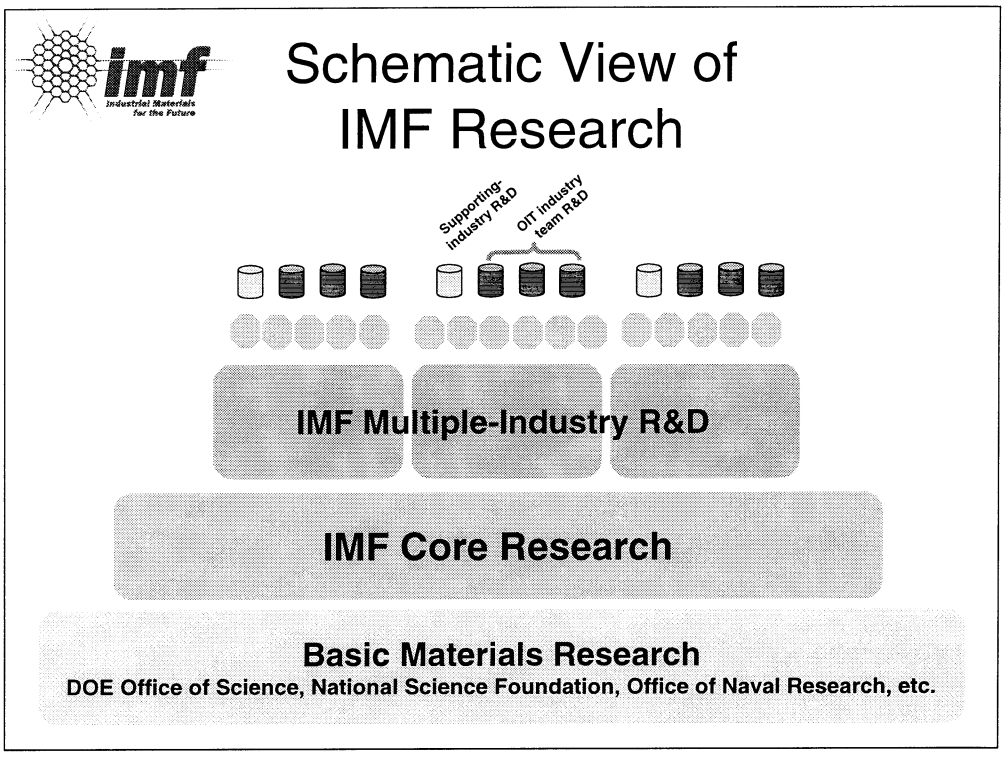


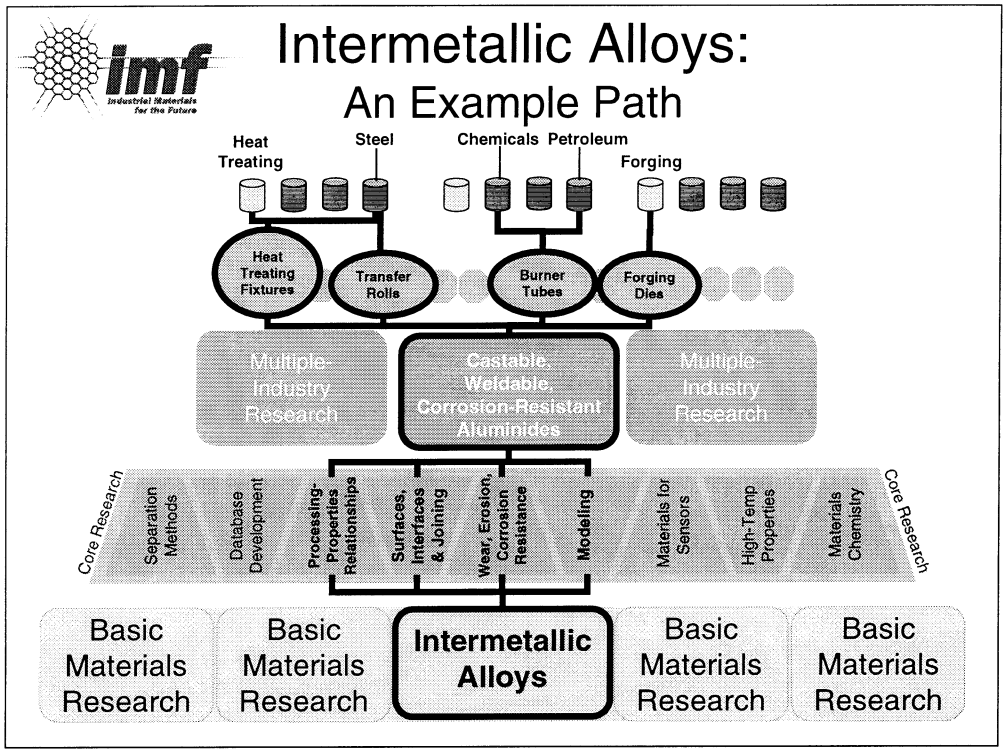
This slide schematically indicates the position and role of IMF research in the continuous spectrum from basic research to near-term R&D directed toward solving the problems of specific industries.

The block at the bottom of the figure represents basic materials research that seeks only to advance the state of scientific knowledge about materials, under the sponsorship of various agencies, including the DOE Office of Science, the Office of Naval Research, the Air Force Office of Scientific Research, the Army Research Office, and the National Science Foundation.

The next block up represents IMF core research, which builds on the results of this basic research to investigate new materials regimes, properties, and processing relationships related to industrial performance needs.

Core research underpins and often leads to IMF multiple-industry R&D that directly addresses the goals and objectives of more than one OIT industry, for example, the development of a new erosion- or corrosion-resistant material. However, this is not necessarily a sequential process, as the multiple blocks indicate.

The next level up represents the many different outputs of IMF multiple-industry research, which, by focusing on and transferring existing projects or developing new projects, are a rich source of OIT industry team and supporting industry R&D, as the top level of the figure indicates.

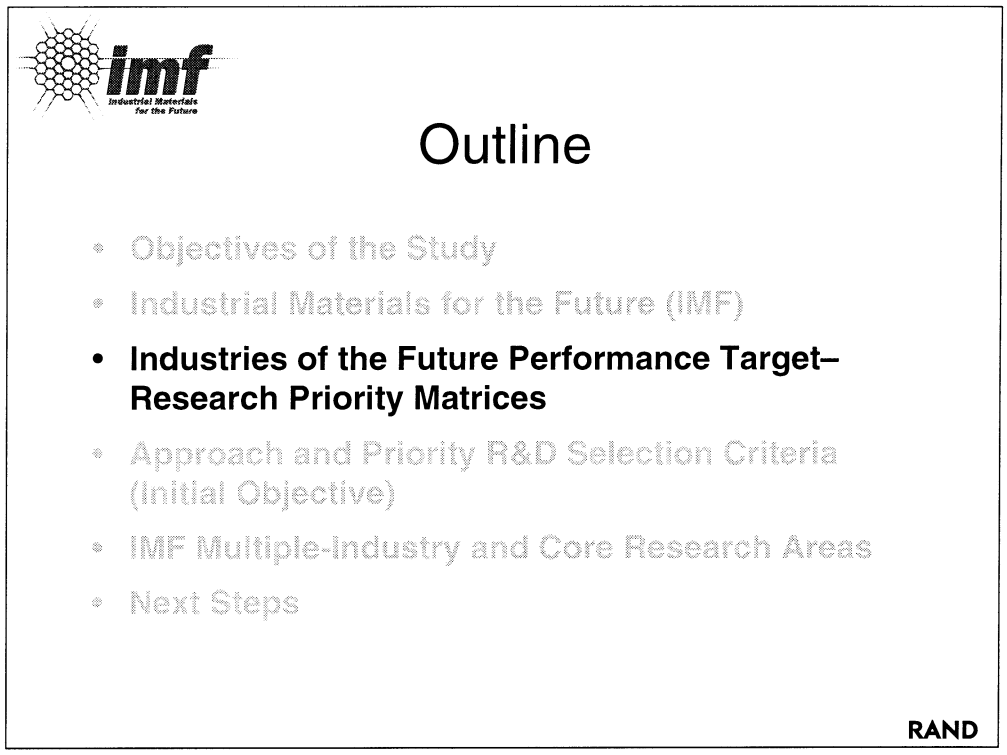


Here, intermetallic alloys demonstrate the path from basic materials research to industrial application. Decades ago, intermetallics, the nickel aluminides in particular, were recognized as promising materials with high strength at high temperature, and their basic material properties were explored. However, principally because these materials had low ductility and a tendency to creep at high temperatures, applications were not pursued.

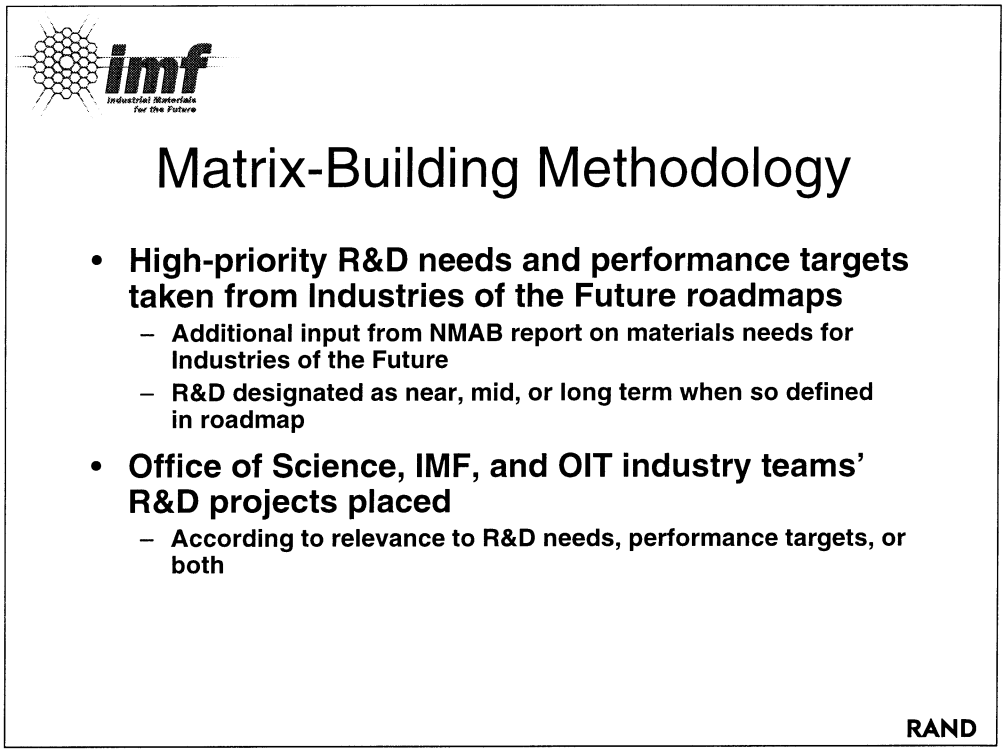
Beginning in 1981 with discretionary funding from Oak Ridge National Laboratory and continuing with support from the Office of Science, IMF's predecessor programs, and DOE's Office of Fossil Energy, a comprehensive research and development program has overcome significant technical barriers to produce industrially useful intermetallic alloys. Since the early 1990s, IMF's predecessor, AIM, focused on composition-processing-properties relationships, with an emphasis on corrosion resistance. The focus was on understanding the causes of low ductility and high-temperature creep, as well as another key problem for industrial use: difficulty of welding. This core research led to the development of castable, weldable, corrosion-resistant aluminide materials that have been the focus over the past several years of AIM (IMF) projects with application to multiple OIT industries.

Within the past few years, these projects have spawned several industrial applications: fixtures for the heat-treating and steel industries, transfer rolls for the steel industry, burner tubes for high-temperature processing for the petroleum and chemical industries, and dies for the forging industry.

The IMF core and multiple-industry research on intermetallics continues, with expected applications for additional Industries of the Future.



The next few slides describe the process RAND used to develop matrices of Industries of the Future performance targets and R&D priorities that indicate in which areas the DOE Office of Science, IMF, and the OIT industry teams are currently sponsoring work.



The basic data for this study consisted of the set of OIT Industry Team vision documents and technical roadmaps (see the OIT Web site: http://www.oit.doe.gov). Additional data came from the National Academy of Science National Materials Advisory Board's (NMAB's) recent review of Industries of the Future materials needs.[1]

The performance targets for each Industry of the Future were from the appropriate technical roadmaps. Each roadmap identified a large number of R&D needs, some of which required materials R&D. The matrix includes needs that required materials R&D and that the industry's roadmap indicated had high priority. The matrix also includes R&D needs that the NMAB review identified as having high priority. When the roadmap indicated the time frame of the R&D, the matrix also includes this information.

RAND reviewed the R&D portfolios of existing OIT programs and the DOE Office of Science (OS), categorizing the programs on the matrix as OS, IMF, and Vision Team (VT)[2] R&D. OIT's Inventions and Innovation (I&I) program was listed in the IMF column because its objectives are similar. [3]

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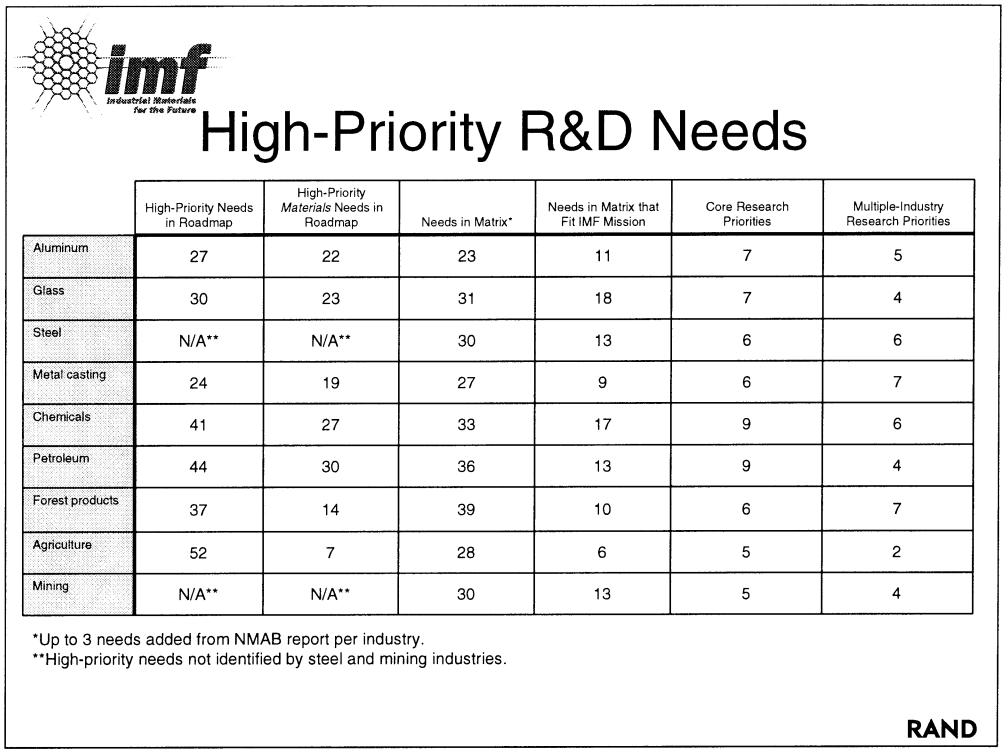
[1]NMAB, *Materials Technologies for the Process Industries of the Future: Management Strategies and Research Opportunities*, Washington, D.C.: National Academy Press, NMAB-496, 2000.

[2]*Vision team* (VT) is an older term for the OIT industry teams; the abbreviation is used in the matrices and is therefore retained here.

[3]Data sources for the matrix were as follows: Energy Materials Coordinating Committee (EMaCC), *Annual Technical Report, Fiscal Year 1999*, DOE/SC-0025, October 31, 2000; Materials Sciences Programs, Fiscal Year 1997, DOE/SC-0001, October 1998; OIT Web site.



	High-Priority Needs in Roadmap	High-Priority *Materials* Needs in Roadmap	Needs in Matrix*	Needs in Matrix that Fit IMF Mission	Core Research Priorities	Multiple-Industry Research Priorities
Aluminum	27	22	23	11	7	5
Glass	30	23	31	18	7	4
Steel	N/A**	N/A**	30	13	6	6
Metal casting	24	19	27	9	6	7
Chemicals	41	27	33	17	9	6
Petroleum	44	30	36	13	9	4
Forest products	37	14	39	10	6	7
Agriculture	52	7	28	6	5	2
Mining	N/A**	N/A**	30	13	5	4

*Up to 3 needs added from NMAB report per industry.
**High-priority needs not identified by steel and mining industries.

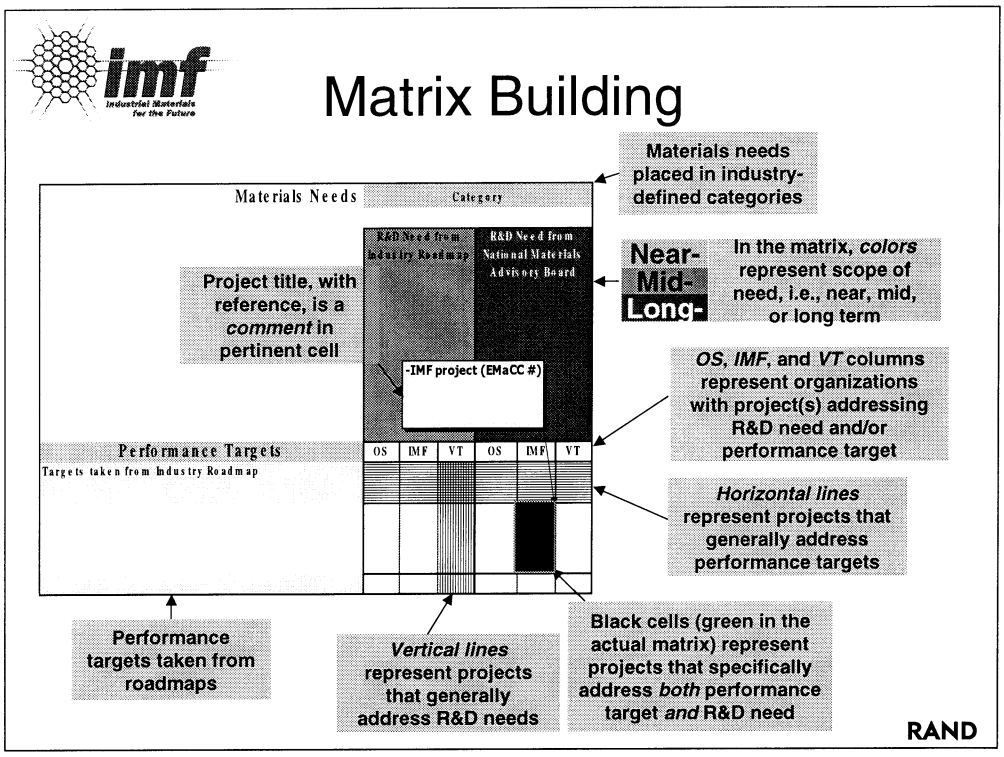
This slide shows that a significant proportion of the high-priority R&D needs that emerged from the Industries of the Future technical roadmaps requires materials R&D. Each industry used a unique priority identification scheme for R&D needs. There were, however, four general types of identification schemes, for which RAND used three different methodologies for the selection of high-priority needs, as explained below. Core research and multiple-industry research priorities are addressed in later slides.

Aluminum, glass, and chemicals used symbols to indicate technical roadmap committee votes for high-, medium-, or low-priority R&D needs. To form an aggregate ranking of each R&D need, symbols were translated to numbers: high = 3, medium = 2, and low = 1. The numbers were then summed for each need, and needs with a score of three or higher were designated as high priority.

Metal casting listed selected high-priority research needs in a summary table at the beginning of its roadmap. All these needs are in the metal casting matrix.

Petroleum, forest products, and agriculture used general labels indicating groups of high-, medium-, and low-priority needs. All high- and medium-priority needs were designated as high priority.

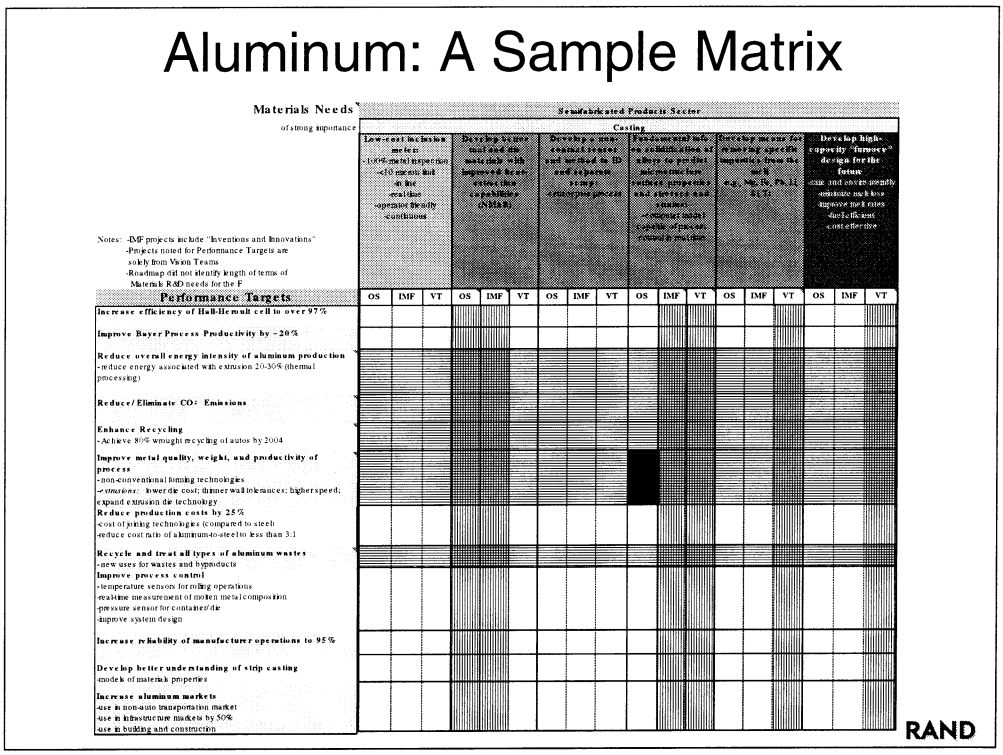
Steel and mining did not prioritize R&D needs. All mining materials R&D needs are in the matrix. However, steel identified hundreds of needs, and in this case, RAND chose only materials needs for the matrix.



This slide illustrates the process RAND followed to build a matrix for each of the nine Industries of the Future. The rows consisted of performance targets taken from the appropriate roadmap. The columns consisted of materials R&D needs that ether the roadmap or the NMAB report identified as high priority, with colors indicating near-, mid-, or long-term R&D when the source specified.

Each column was subdivided into three to represent R&D on that materials need that was sponsored by the Office of Science, IMF, or the industry teams, which the matrix refers to as VT. Horizontal lines represent projects that addressed the performance targets but were not associated with any particular materials R&D need. Vertical lines represent projects that addressed a particular R&D need but were not directed specifically toward a performance target. Solid green cells in the matrix (which appears as solid black above) represent projects that specifically addressed both a performance target and an R&D need.

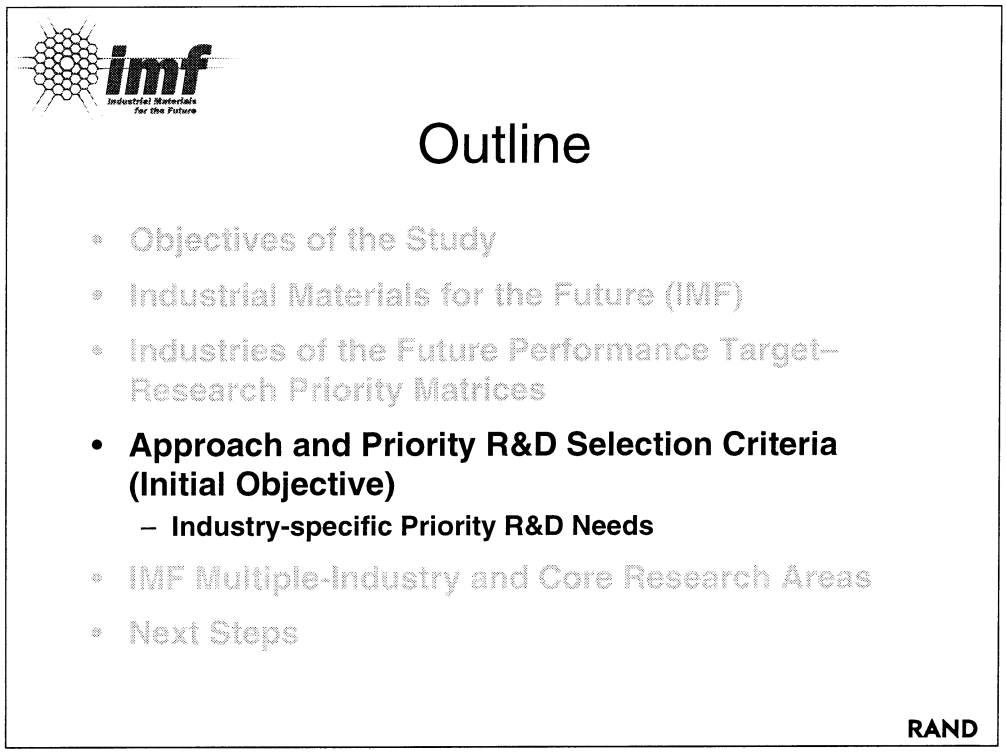
Project titles, with a reference to the source of project data, appear as comments in the appropriate cells of the matrix.



This slide presents page two of the completed seven-page aluminum matrix as an example. The horizontal lines indicate that five of the 12 performance targets have projects addressing them that are not associated with any specific materials research need.

The columns encompass the casting part of the semifabricated products sector of the aluminum industry roadmap and indicate that work is ongoing in the Office of Science and IMF on tool and die materials (an NMAB-identified mid-term priority) and in all three programs on modeling of microstructure-properties relationships (with OS work also focused on a performance target). They also indicate OIT industry team work on removing impurities from the melt and on a high-capacity furnace design (a long-term priority).

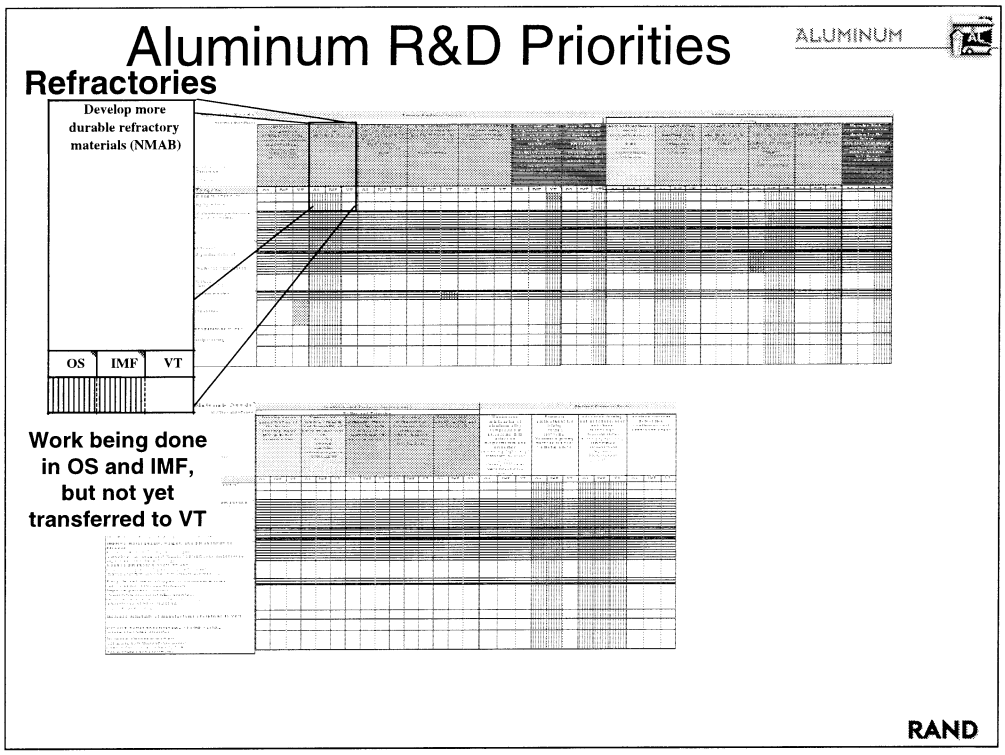
The other pages of the matrix include columns for the primary products sector, rolling and extrusion in the semifabricated products sector, and the finished products sector and project listings according to cells of the matrix and the source of the project data.



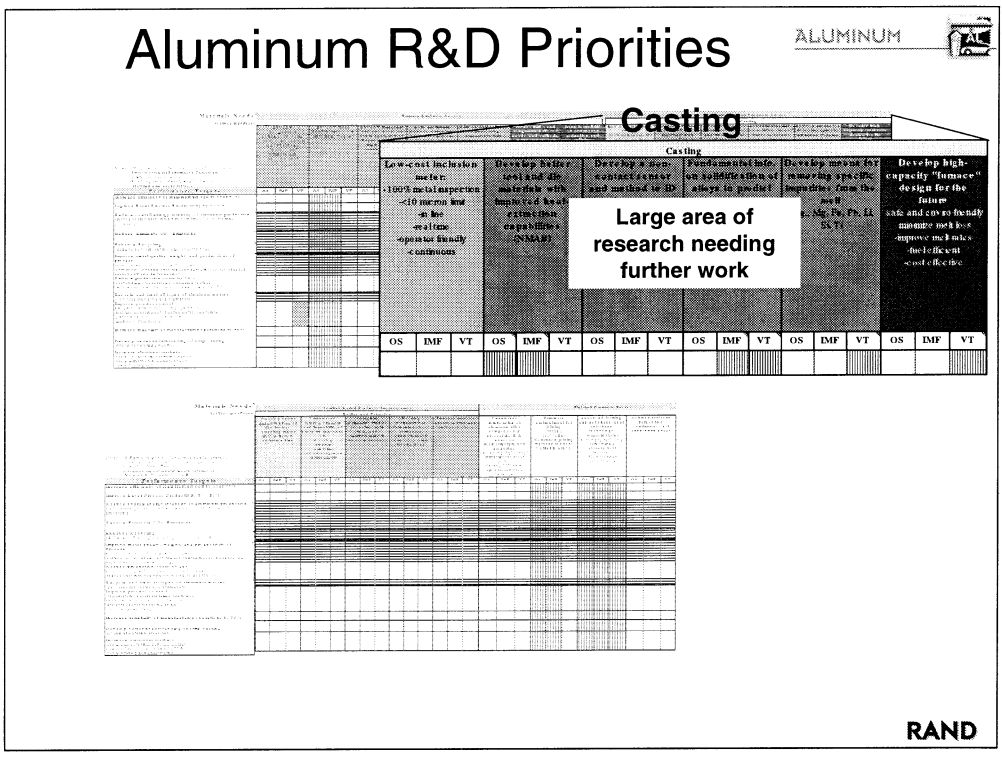
This section of the documented briefing describes RAND's approach to using the performance target–research priority matrices to identify which priority materials R&D needs of the nine Industries of the Future are consistent with the IMF mission. The aluminum matrix again illustrates the process. The section also presents the materials R&D priorities RAND identified from the matrices for each of the industries.

To identify materials R&D priorities for each OIT industry, RAND began by reviewing the vision statements, technical roadmaps, and other relevant documents, such as the NMAB report, then based the performance target–research priority matrices on the data in these documents.

The next step was to identify materials R&D activities that are both high priority for the OIT industries (i.e., address materials R&D needs specified in the matrices) and are consistent with the IMF mission. This dictated emphasizing less-mature technologies and research having the potential to provide combinations of properties not found in existing commercial materials. Areas in which the industry teams already sponsor research were ruled out, unless there was a clear need for additional core research or multiple-industry research to provide new materials technology options for future industry team efforts.

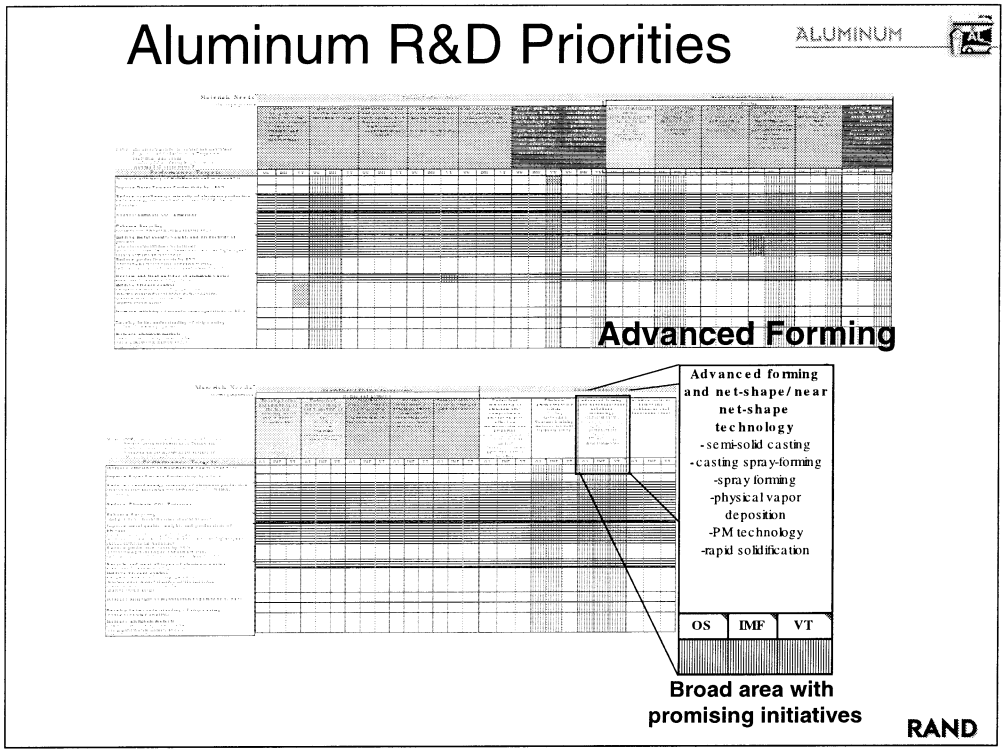


Still using the aluminum matrix as an example, the NMAB report made a strong case for the need to develop more-durable refractory materials, especially to contain and transfer molten metal in melting and casting in both the primary and secondary (remelt or recycling) sectors. The matrix shows that the Office of Science (Basic Energy Sciences Materials Program) and the IMF are doing work in this area, but it has not yet been transferred to the aluminum industry team. Thus, refractory materials is an area of continued emphasis for IMF.

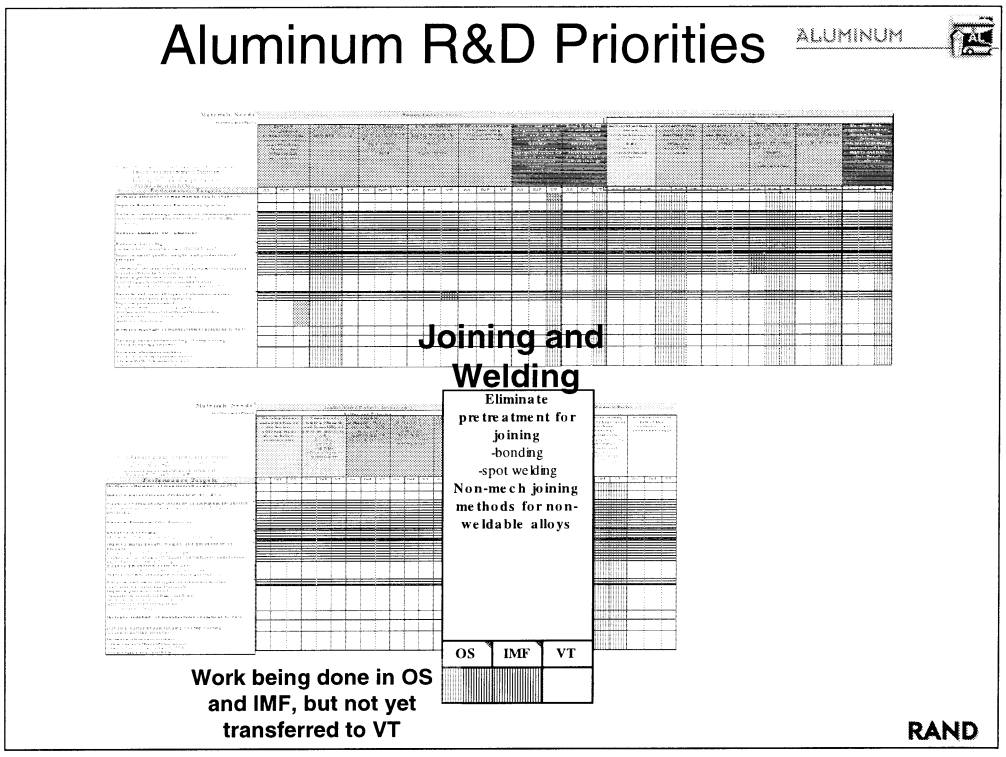


The aluminum matrix also identifies several areas of casting research as having high priority, including improved tool and die materials and research on the solidification of alloys to predict microstructure, surface properties, and stresses and strains. The last area emphasizes computer modeling and process control. The Office of Science and IMF are both working in these areas, and the industry team has a project on semisolid alloys. Both areas have broad potential impact and are worthy of continued IMF effort.

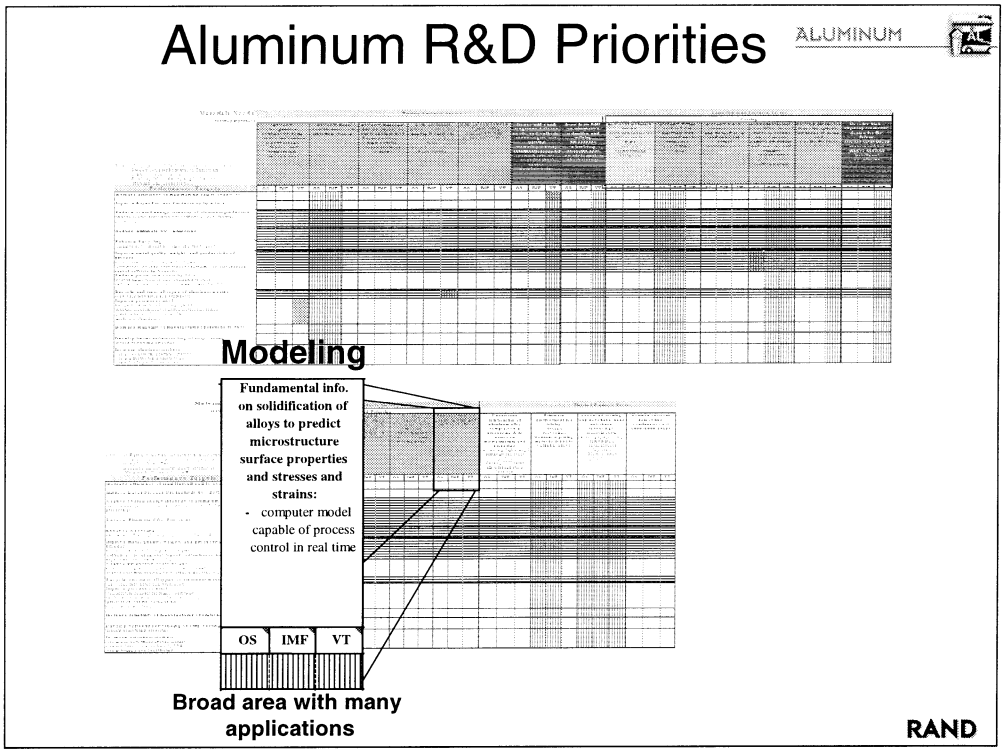
On the other hand, the industry team is working on methods for removing specific impurities from the melt and on developing a high-capacity furnace design, both of which are specific to the industry and not appropriate for IMF.



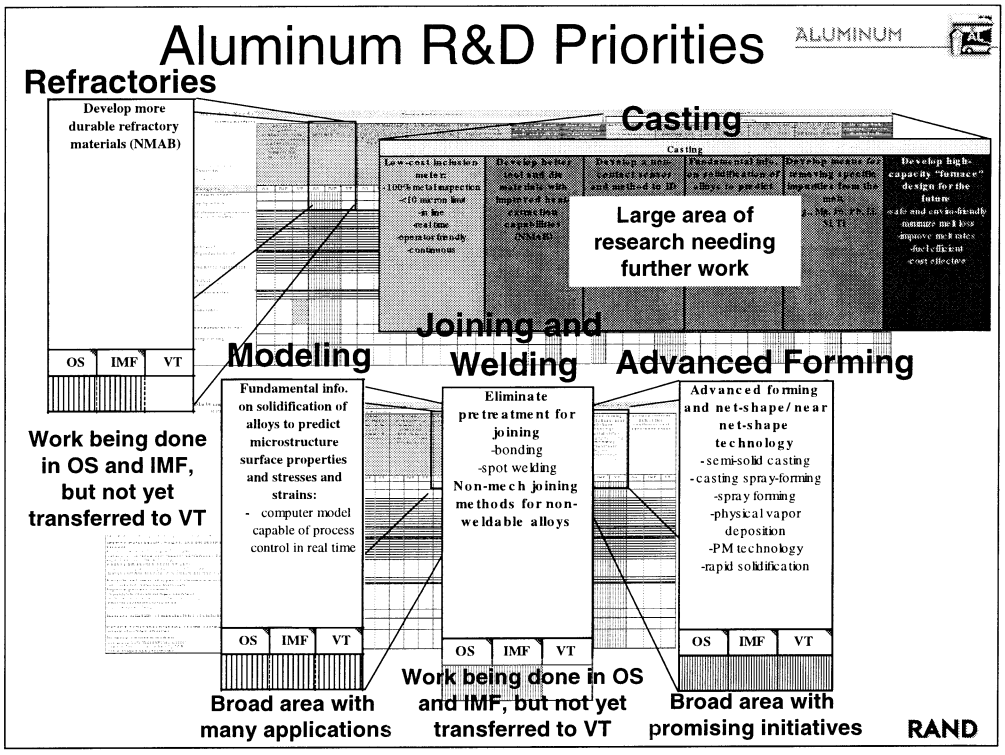
Another area in which the aluminum matrix indicates the Office of Science, IMF, and the industry team are working is advanced forming techniques, which include net-shape and near net-shape technology. This is another broad area with several promising initiatives, including semisolid casting, spray forming, infrared heating, physical vapor deposition, powder metallurgy, and rapid solidification. Continued IMF research on advanced forming methods has the potential to provide new product opportunities for the aluminum and steel industries and useful materials for many of the other Industries of the Future. An example would be spray forming of erosion-resistant coatings. Thus, advanced forming is another IMF research priority.



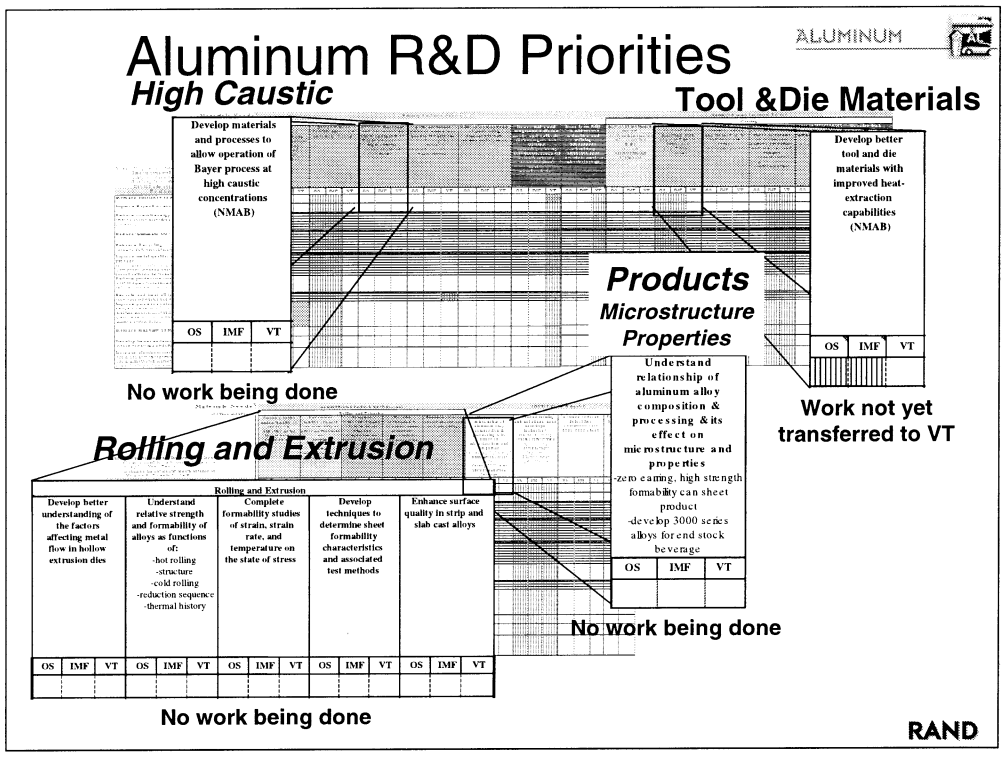
Welding and joining is another area the aluminum matrix identified as having priority, both in the development of alloys that can be joined without extensive surface treatment and in the development of welding and joining methods. There is ongoing work in both the Office of Science and IMF that has not yet been transferred to the aluminum OIT industry team.



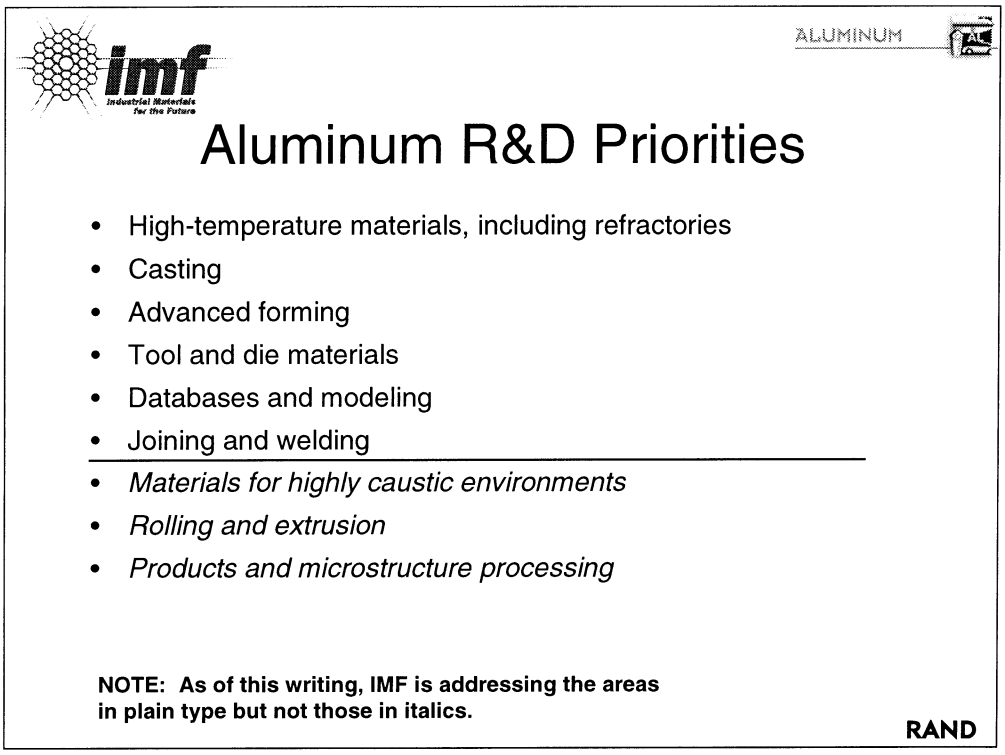
As noted previously, computer modeling of the solidification process can provide the information needed to develop real-time process-control methods. Development of databases on materials properties would improve understanding of composition-processing-properties relationships. In turn, using the data in detailed process models could lead to improved products, new materials capabilities, and better quality control. Thus, database development and modeling are continuing high-priority areas for IMF.



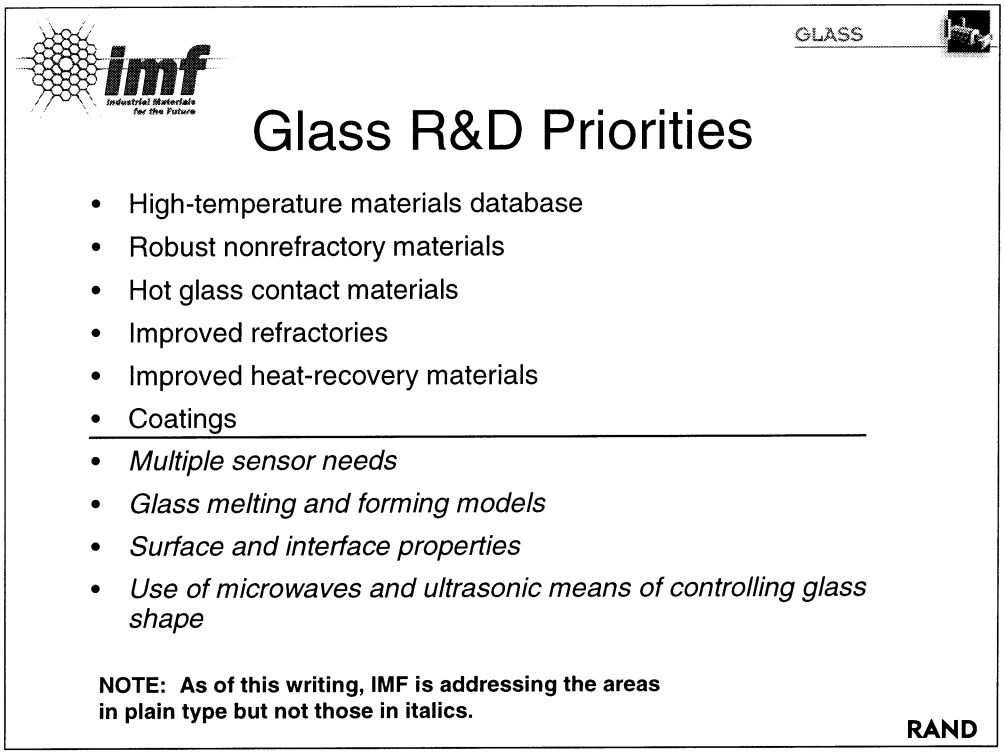
This slide summarizes five of the high-priority IMF materials R&D areas RAND identified from the aluminum matrix and the reasons for so identifying them. IMF research is going on in all of these areas and should continue.



This slide shows additional high-priority areas RAND identified from the aluminum matrix in which no research is currently going on. The NMAB report noted the need for materials and processes to allow the operation of the Bayer process for obtaining alumina from bauxite at higher caustic concentrations to increase productivity. The aluminum roadmap described several research priorities in rolling and extrusion, focusing on improving process modeling and understanding to improve yield and product quality. The roadmap also noted the importance of understanding the relationship between aluminum alloy composition and processing and understanding the effect of the relationship on microstructure and properties, especially in the finished-products sector. These are all high-priority areas for IMF research. As noted previously, tool and die materials are a continuing area of priority for IMF research.

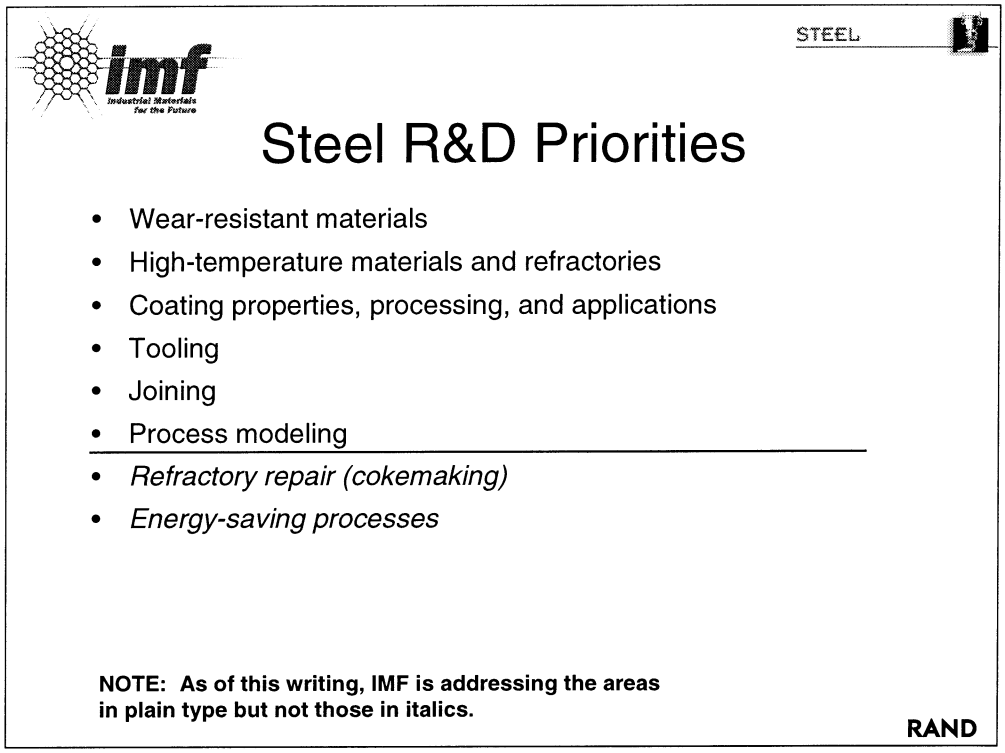


These IMF R&D priorities are from the aluminum performance target–research priority matrix. The areas that IMF is addressing as of this writing appear above the solid line, in plain type. Those IMF is not currently addressing appear below the line and are in italics.



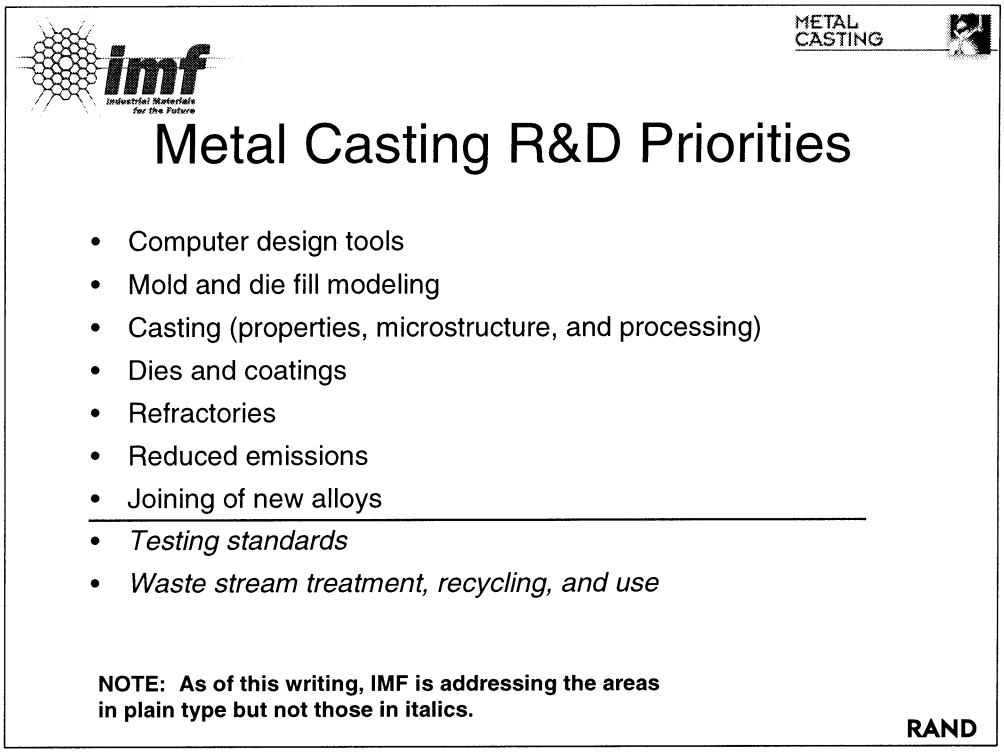
This slide summarizes the IMF R&D priorities from the glass performance target–research priority matrix. High-temperature materials data is central to ongoing IMF and glass industry team efforts to identify new materials with improved properties for glass furnace applications, including hot-glass contact materials, refractories, and nonrefractories. Materials for heat recovery and coatings to extend furnace materials life are also critical areas in which both groups will continue work to reduce process energy use by 50 percent and production costs by 25 to 50 percent from 1995 levels by 2020.

Several high-priority materials research areas in the glass matrix that IMF is not addressing as of this writing would be appropriate new thrusts. These include sensor materials that can withstand the glass furnace environment, the development of glass melting and forming models, and core research on understanding surface and interface properties. Another area of possible interest is to build upon existing IMF research to explore the use of microwave and ultrasonic methods to control glass shape.



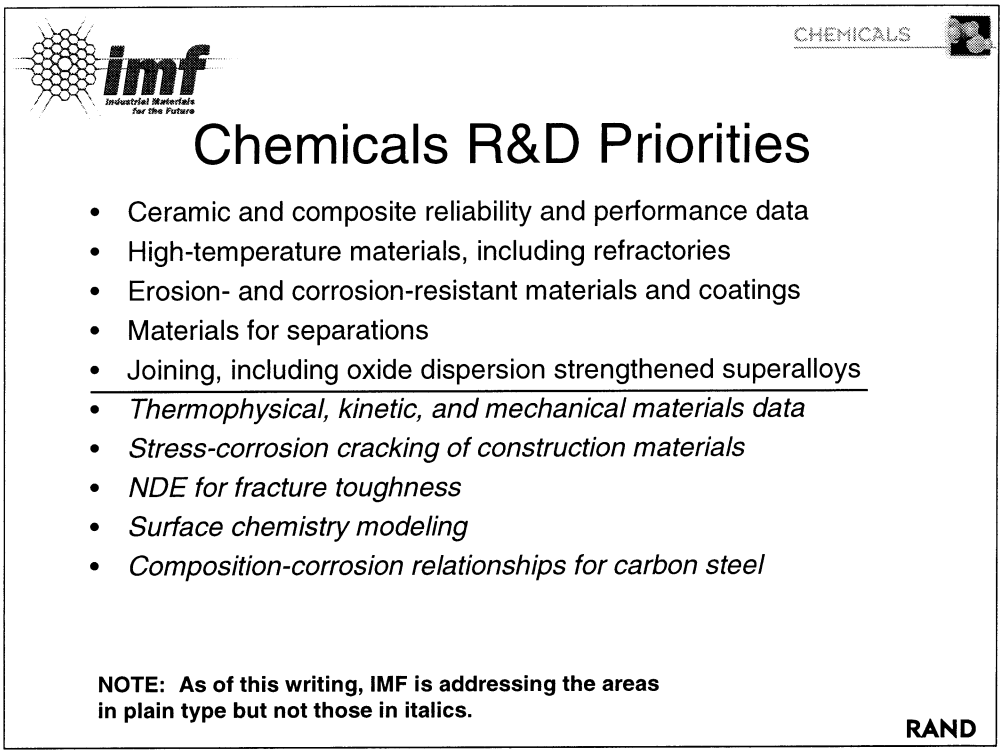
The IMF R&D priorities from the steel performance target–research priority matrix appear above. Wear-resistant high-temperature materials is a high-priority area for continued IMF emphasis, as are development, characterization, and application of coatings, both for process equipment and products. Tooling and joining are additional areas IMF is pursuing as of this writing in the steel-product development sector. Process modeling is an important core research area supporting these activities.

Two areas IMF is not currently addressing emerged from the matrix review as potential new thrusts: refractory repair technology for cokemaking furnaces and the development of new energy-saving processes for electric arc furnace steelmaking (e.g., superconducting electrodes, high-power induction melting, and microwave processing).



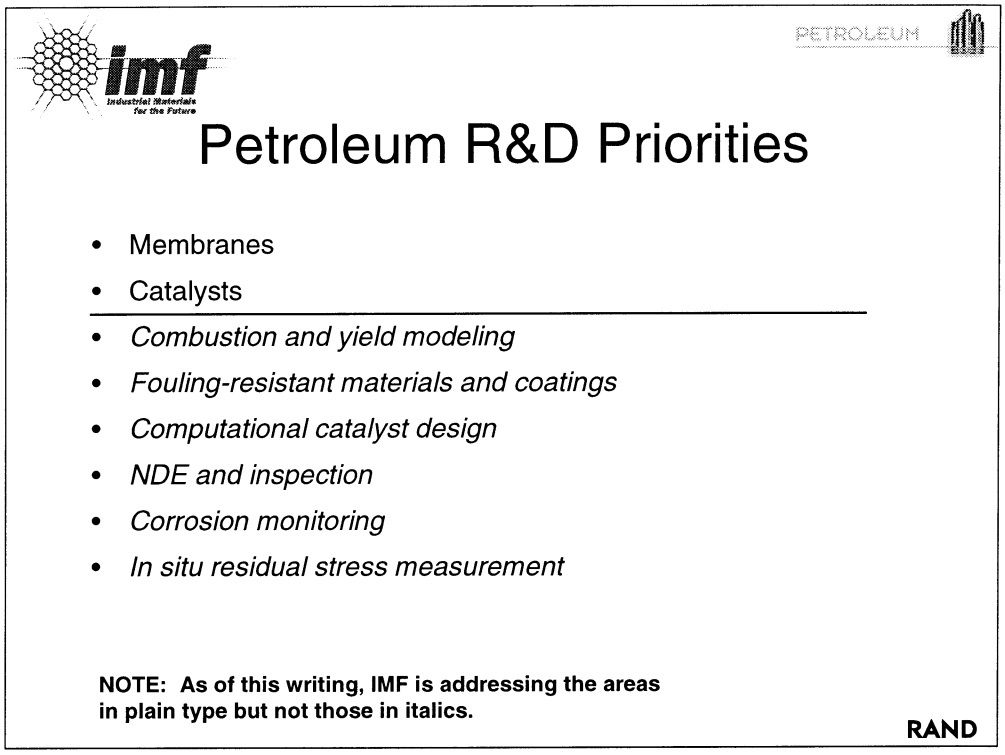
This slide summarizes the IMF R&D priorities from the metal casting performance target–research priority matrix. The development of computer design tools and models, an improved understanding of mold and die filling, and quantitative relationships between alloy chemistries, properties, microstructure, and processing of castings are underpinning research areas in which IMF is involved as of this writing. Improved die and coating materials and refractories are additional high-priority areas to be continued, as are the development of environmentally benign, dimensionally stable molding materials for sand casting and the development of joining methods for new alloys.

Additional high-priority research areas that IMF is not currently addressing but should consider for new thrusts are establishing standard methods for materials testing and the development of new uses for waste streams and new ways to treat wastes to make them more useable.



As of this writing, IMF is addressing several of the high-priority research needs in the above list from the chemicals performance target–research priority matrix. These include performance and reliability of ceramics and composites in processing equipment; development of high-temperature materials with improved properties, including refractories; development of erosion- and corrosion-resistant materials and coatings, including intermetallics and ceramic composites; separation materials, including membranes with designed pore structures and zeolite–sol-gel composite thin films; and joining ceramics and high-temperature metal alloys.

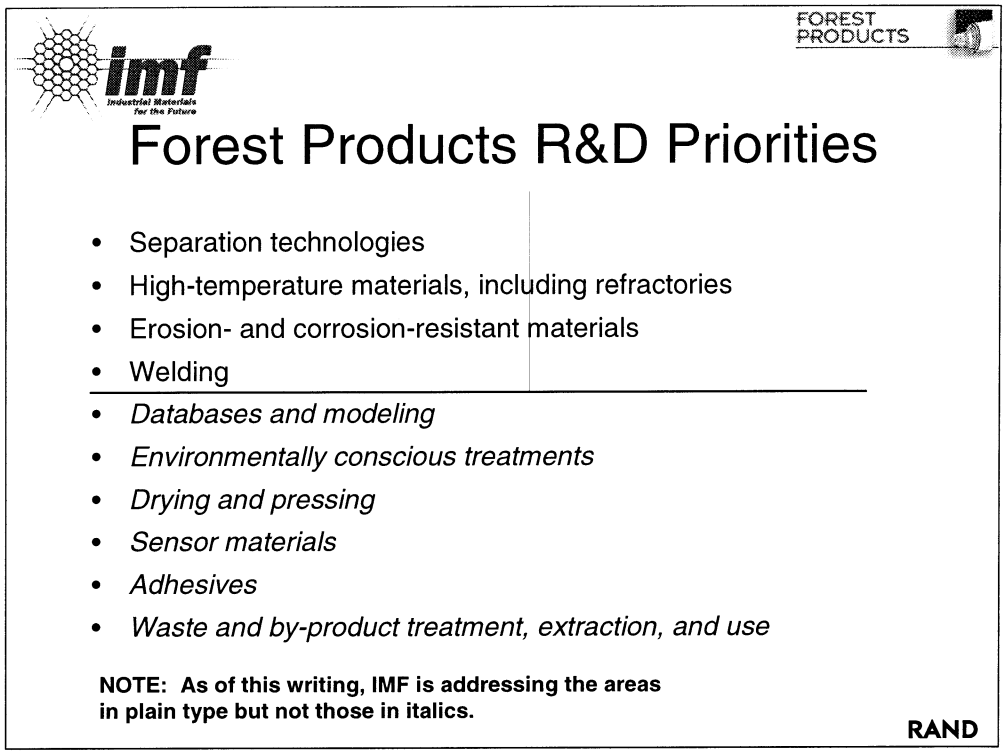
The matrix yielded several additional high-priority research areas that could form new IMF thrusts, including thermophysical, kinetic, and mechanical materials data that support chemical process design and choice of materials for process equipment, stress-corrosion cracking of construction materials for chemical process equipment, nondestructive evaluation (NDE) methods focused on fracture toughness, modeling of surface chemistry to identify catalysts and construction materials, and determination of the effects of composition on corrosion of carbon steel used in process equipment.



This slide summarizes the IMF R&D priorities from the petroleum performance target–research priority matrix. As of this writing, IMF is addressing two research areas that deserve continued effort: development of advanced membranes for hydrocarbon separation and catalysts for diesel desulfurization.

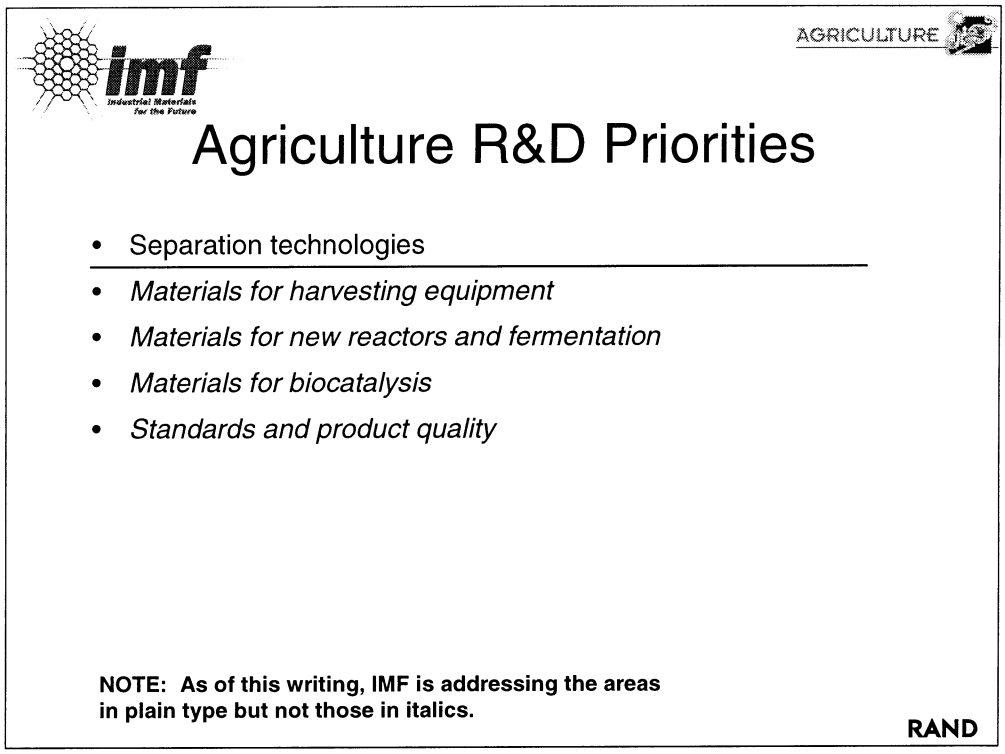
Several high-priority research areas in the petroleum matrix appear to be appropriate for new IMF thrusts, including fouling-resistant materials and coatings for equipment operating at temperatures in excess of 500°C, computational materials science focused on catalyst design, NDE and inspection methods, corrosion monitoring, and in situ residual stress measurement of processing equipment.

All the priority research areas that IMF is pursuing as of this writing that appear in the chemicals matrix and on the previous slide are also relevant to the petroleum industry, even though the petroleum matrix does not identify these areas. For example, IMF research on castable, weldable, corrosion-resistant nickel aluminides led to the development of burner tubes for both the chemicals and petroleum industries.



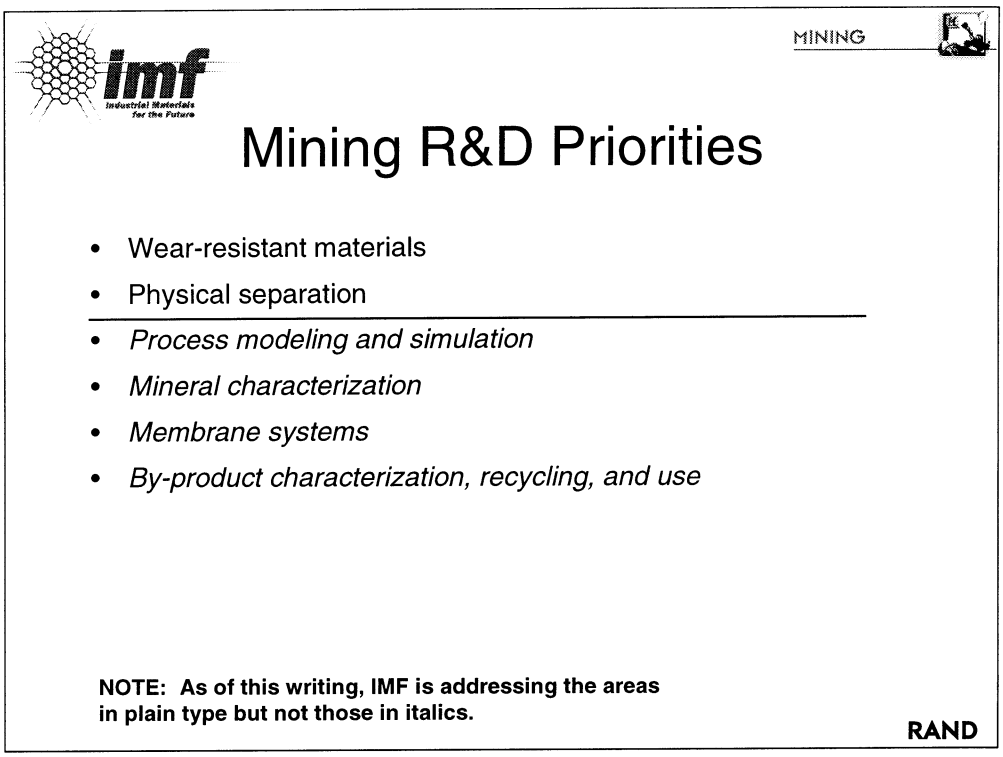
This slide summarizes the IMF R&D priorities from the forest products performance target–research priority matrix. Office of Science (Small Business Innovation Research [SBIR]), IMF, and OIT industry team research is addressing development of separation methods to remove contaminants and clean remaining discharges. This continues to be an important area for IMF, building upon core research in membrane and filtration materials. High-temperature materials, including refractories, and erosion- and corrosion-resistant materials that can withstand the hostile environment of pulp and paper processing are another priority IMF is addressing as of this writing. Another such area is welding of new materials for system fabrication and construction.

The forest products matrix suggests several additional high-priority research areas that fit IMF's mission. Databases and modeling are needed for the development of low-effluent processes and environmentally conscious treatment methods. Research is needed to develop new low-cost, high-efficiency drying and pressing methods. New sensor materials are needed to improve process control and better adhesives to improve product quality. Finally, increased understanding of waste and by-product streams and the development of effective means of treating, extracting, and using by-products would advance the industry toward its performance objective of environmental harmony.



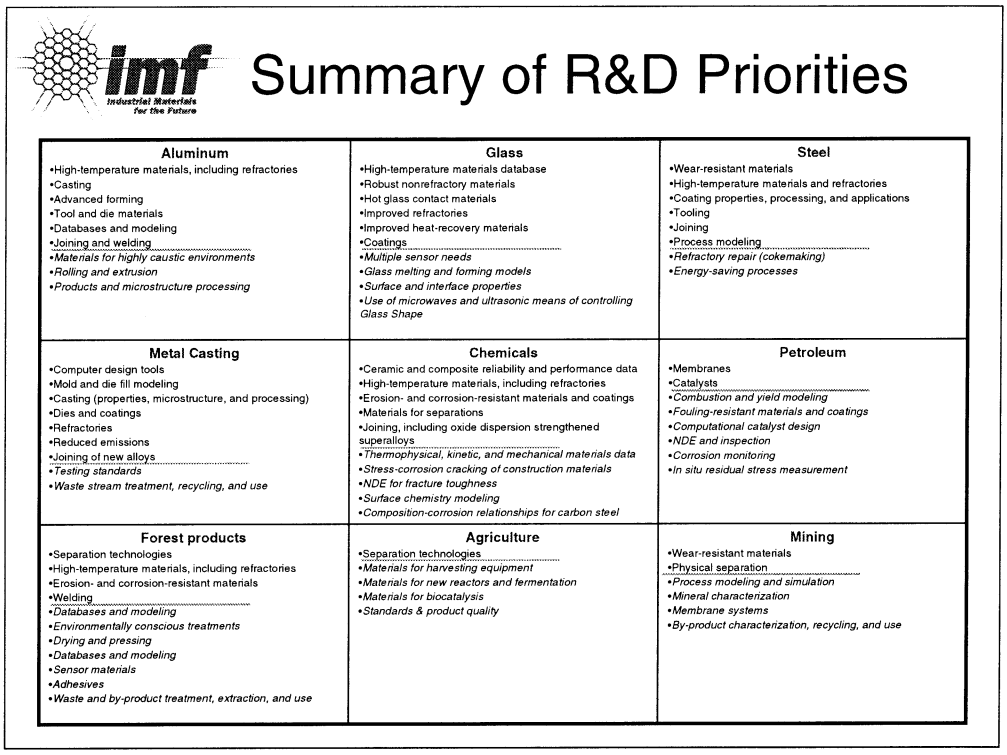
This slide summarizes the IMF R&D priorities from the agriculture performance target–research priority matrix. Membranes for separations is an ongoing priority research area for the Office of Science (SBIR), IMF, and the agriculture OIT industry team.

The matrix also identified a number of additional research areas that could form new IMF thrusts, including materials for harvesting equipment, reactors, fermentation equipment, and biocatalysts. The development of standards and analytical methods to support product quality is an area in which IMF could provide strong insights and expertise.

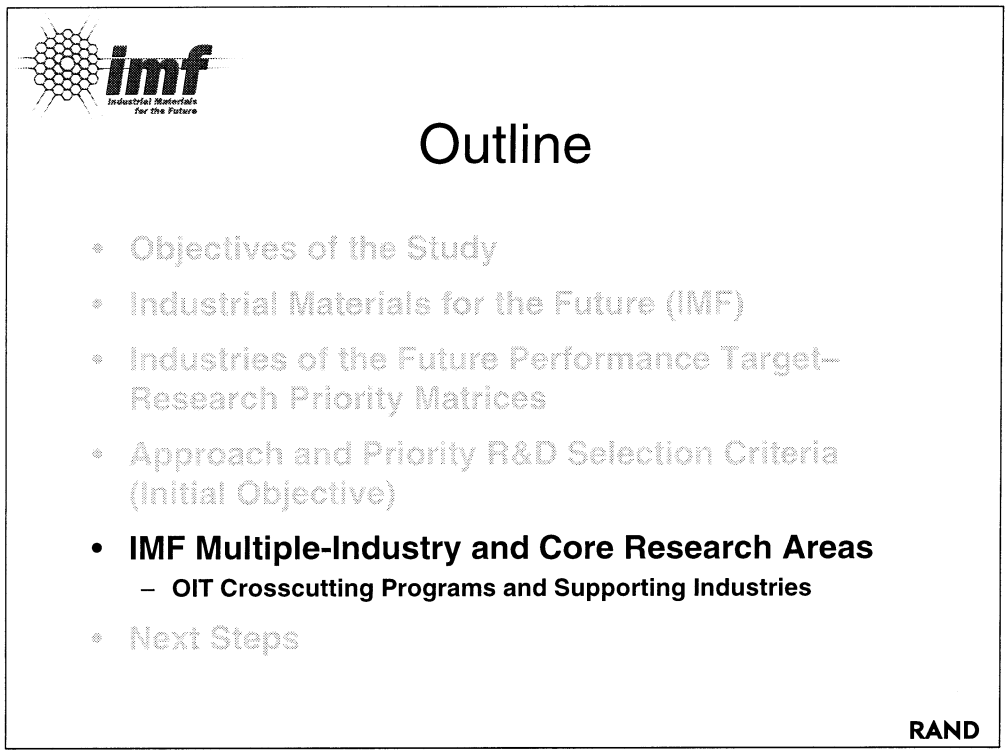


This slide summarizes the IMF R&D priorities from the mining performance target–research priority matrix. Wear-resistant materials is a current area of emphasis, with Office of Science, IMF and OIT industry team research aimed at extending the life of surfaces by 40 percent. Physical separations is another area in which OIT-sponsored work consistent with the IMF mission is being pursued, in this case under the National Industrial Competitiveness through Energy, Environment and Economics (NICE^3) program.

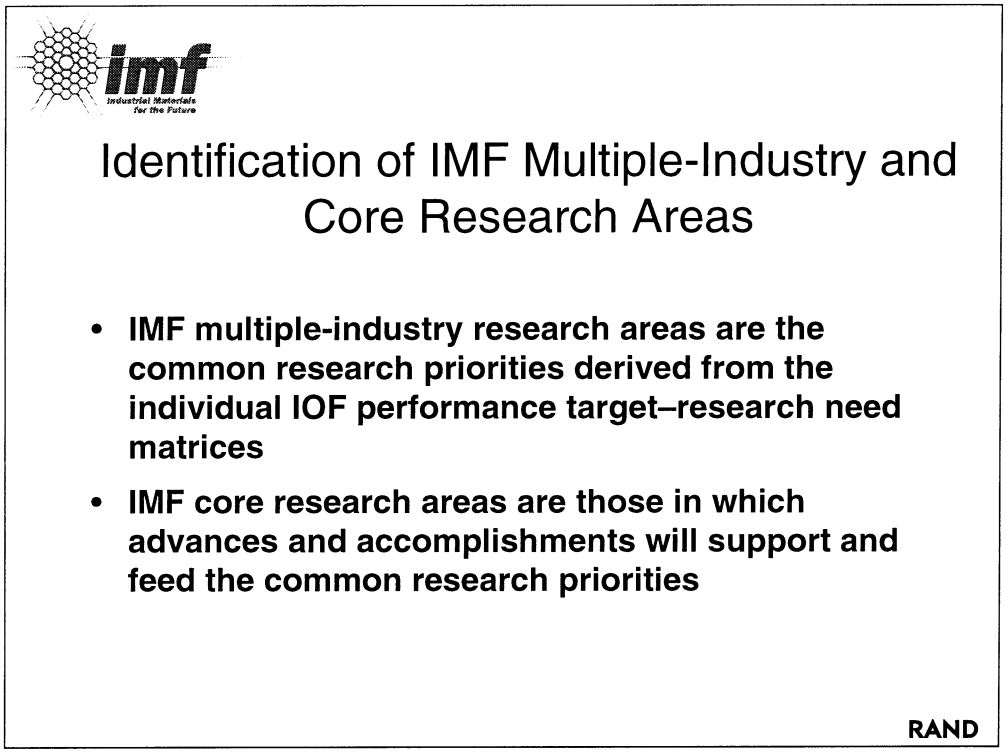
Several priority research areas this matrix identifies could be the basis for new IMF thrusts. These include process modeling and simulation in such areas as fracture and wear, crushing and grinding, rock disintegration, characterization of mineral deposits to increase yield and productivity, development of new membrane systems for chemical and fine-particle separation, and characterization and understanding of by-products to develop more useable process streams, including recycling.



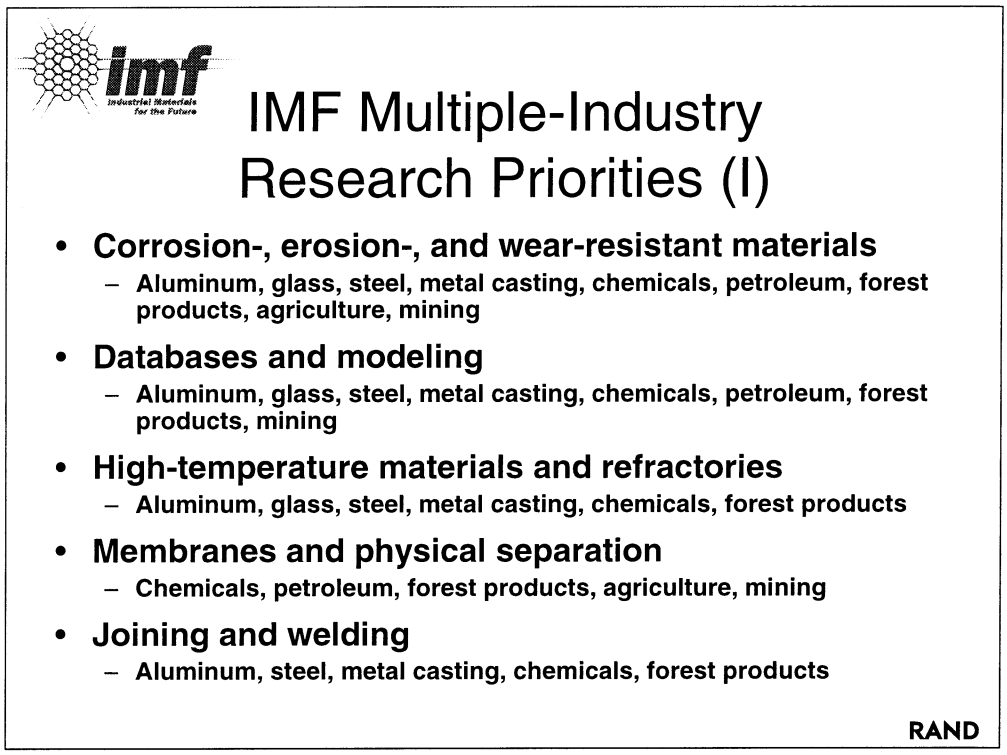
This table summarizes the IMF-consistent materials R&D priorities from the nine Industries of the Future performance target–research priority matrices.



This section of the briefing describes the materials R&D priorities that apply to multiple Industries of the Future and the core research areas that underpin these multiple-industry research priorities. Materials research priorities for the OIT crosscutting programs (Combustion, Sensors and Controls) and supporting industries (heat treating, forging, and welding and joining) are also discussed.



Several IMF R&D priorities that emerged from the review of the nine performance target–research priority matrices apply to more than one of the Industries of the Future and thus form the basis for a research portfolio consistent with the IMF mission. Several core research areas underpin these multiple-industry research priorities, in that advances and accomplishments in these areas are required to achieve the goals of the multiple-industry research. These areas are described in the following slides.



This and the following slide list the multiple-industry research priorities and the industries to which each applies. The first six priorities apply to five or more Industries of the Future; the remaining five apply to four or fewer.

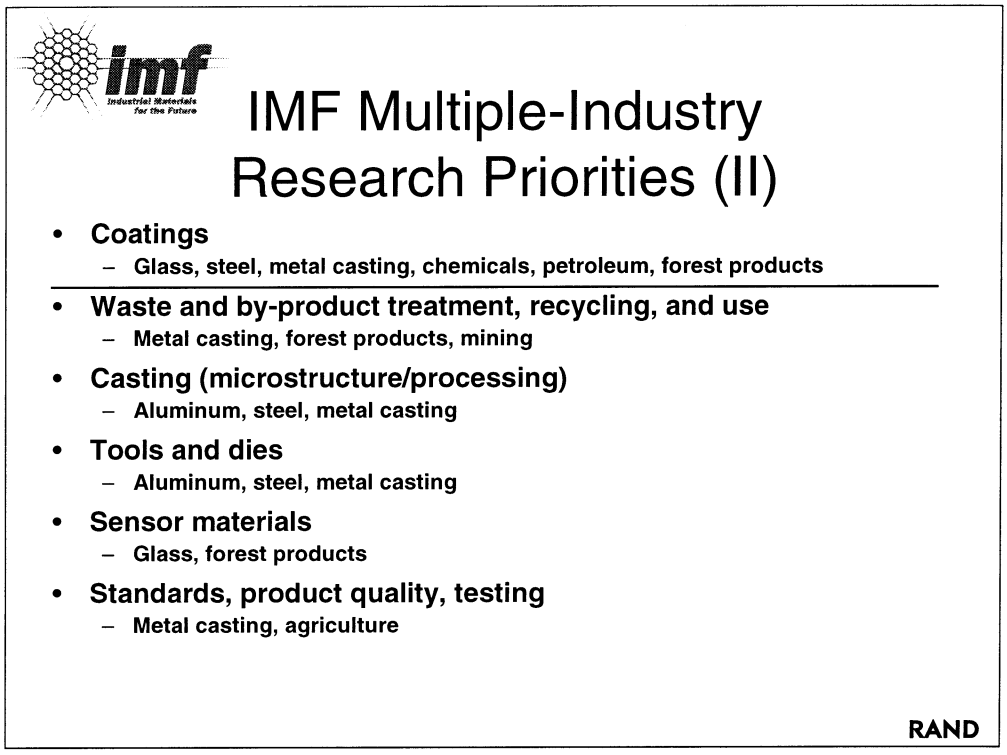
Corrosion-, erosion-, and wear-resistant materials are essential for process equipment in all nine industries; the specific suite of properties depends on the environment of the specific industrial processes.

Databases and modeling of materials properties, especially those required for high-temperature and corrosive-erosive environment service, and of composition-properties-microstructure-processing relationships are fundamental to almost all of the OIT industries.

High-temperature materials, including refractories, are high-priority research areas for all the materials production industries, as well as for forest products and chemicals, both of which involve high-temperature processing.

Membranes and physical separation methods and materials form another IMF priority research area that emerged from the performance target–research priority matrices of five of the nine industries.

Five of the nine matrices had joining and welding for the construction of process equipment and the development of materials that are easily welded and joined without the need for special preparation as a priority.



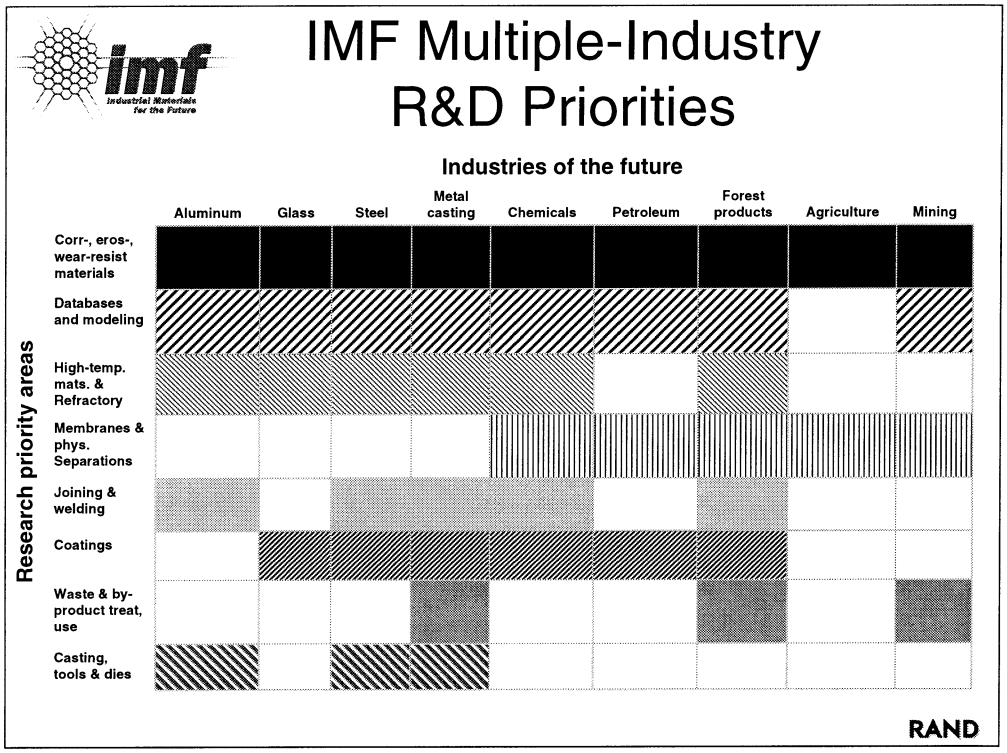
Coatings, both for process equipment in severe environments and for products, are a high-priority area for the glass, steel, metal casting, chemicals, petroleum, and forest products industries.

The research priorities below the solid line on the slide apply to fewer than five (a minority) of the nine Industries of the Future, while all those on the previous slide and the first on this slide apply to a majority of the industries.

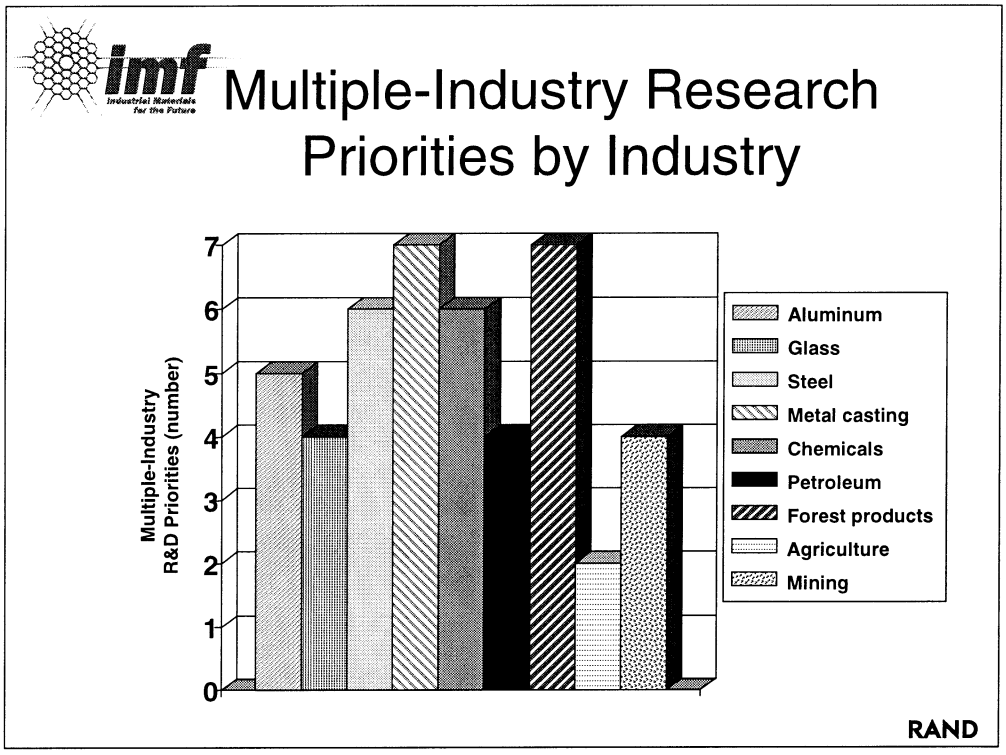
Waste and by-product treatment, recycling, and use is a high-priority area for metal casting, forest products, and mining.

The production of aluminum and steel, as well as metal casting, requires advances in the understanding of microstructure-processing relationships in casting and the development of improved tools and dies.

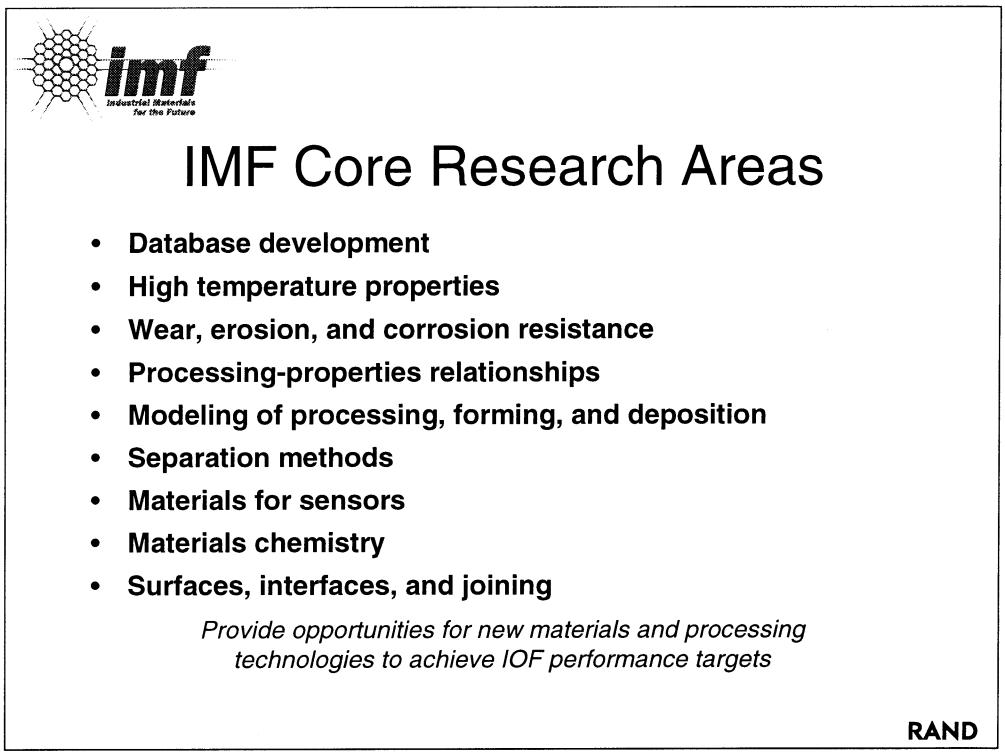
Finally, both the glass and forest products matrices suggest a need for new sensor materials, and the metal casting and agriculture matrices suggest a need for standards and testing to improve product quality.



This matrix summarizes the IMF multiple-industry research priorities the previous slides described. Corrosion-, erosion-, and wear-resistant materials applies to all nine industries, databases and modeling to eight of the industries, high-temperature materials and refractories and coatings to six of the industries. Sensor materials and standards, product quality, and testing each applied to only two of the industries, and thus are not shown.

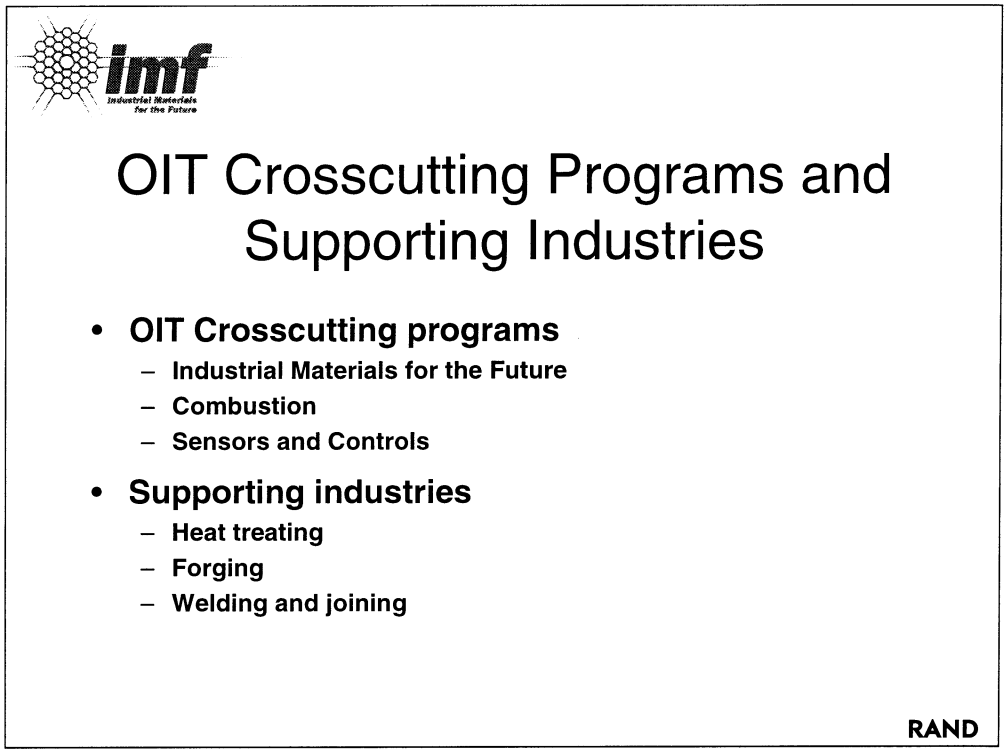


This bar chart indicates the number of the eight multiple-industry research priorities from the previous slide that apply to each Industry of the Future. The number ranges from two for agriculture to seven for metal casting and forest products.

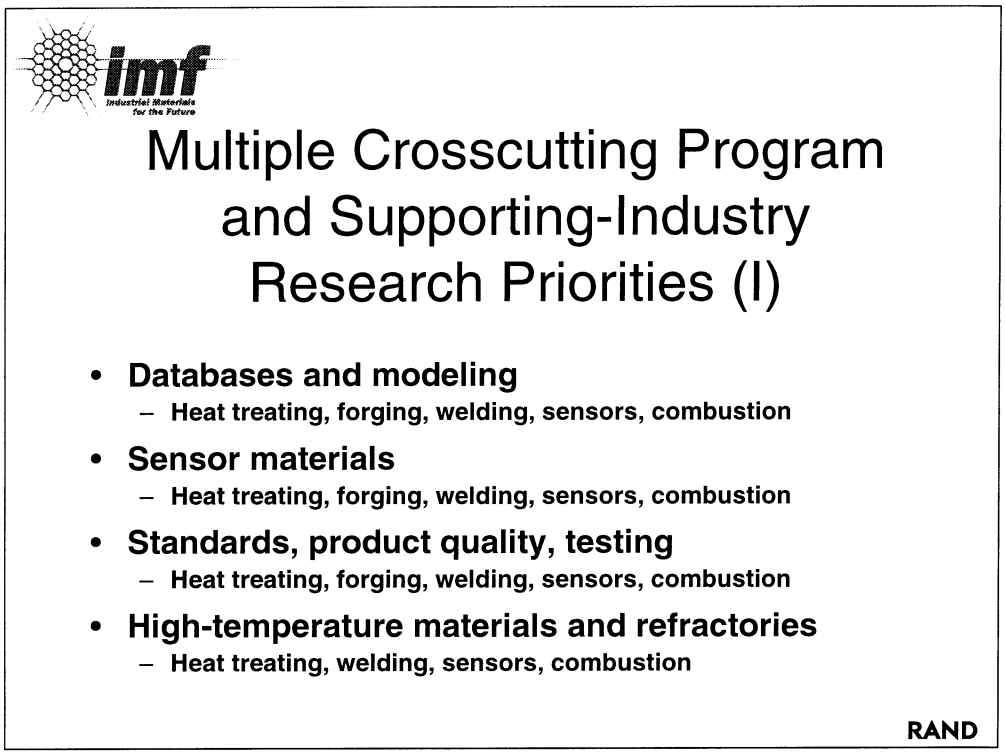


Each IMF multiple-industry research area the previous slides describe requires underpinning core research. For example, the development of erosion- and corrosion-resistant high-temperature materials requires research on high-temperature properties and erosion-corrosion resistance and may well require database development if new regimes or suites of properties are being sought. The example of the high-temperature intermetallic alloys is instructive. Achieving a suite of properties useful for heat treating fixtures, steel transfer rolls, burner tubes, and forging dies required new compositions and new processing methods to develop alloys that were castable, weldable, and corrosion resistant.

This slide lists the core research areas in which IMF research will be required to underpin research in the multiple-industry research areas identified through the review of the industry matrices. The research in these core areas will provide the opportunities to develop new materials and processing technologies to achieve the industry performance targets that depend upon materials research. Each core research area underpins one or more of the multiple-industry R&D areas on the previous slides.



Three OIT programs provide research that supports multiple Industries of the Future. These crosscutting programs are IMF, Combustion, and Sensors and Controls. In addition, OIT has programs in three industrial areas that support the Industries of the Future: heat treating, forging, and welding and joining.



This and the following slide list research priorities for the multiple crosscutting programs and supporting industries, together with the programs and industries to which each applies. RAND based this list on a review of the existing program plans, vision statements, and technology roadmaps of the OIT crosscutting programs and supporting industries and on the identification from these of materials R&D priorities consistent with the IMF mission. While the R&D categories are the same as shown previously for the Industries of the Future, their relative importance is different here. For example, sensor materials and standards, product quality, and testing each apply to only two industries but apply to all five crosscutting programs and supporting industries.

Databases and modeling, including simulations and computational fluid dynamics, are critical needs for prediction of properties resulting from heat treating, forging, and welding and joining, as well as the development of robust sensors and combustion systems.

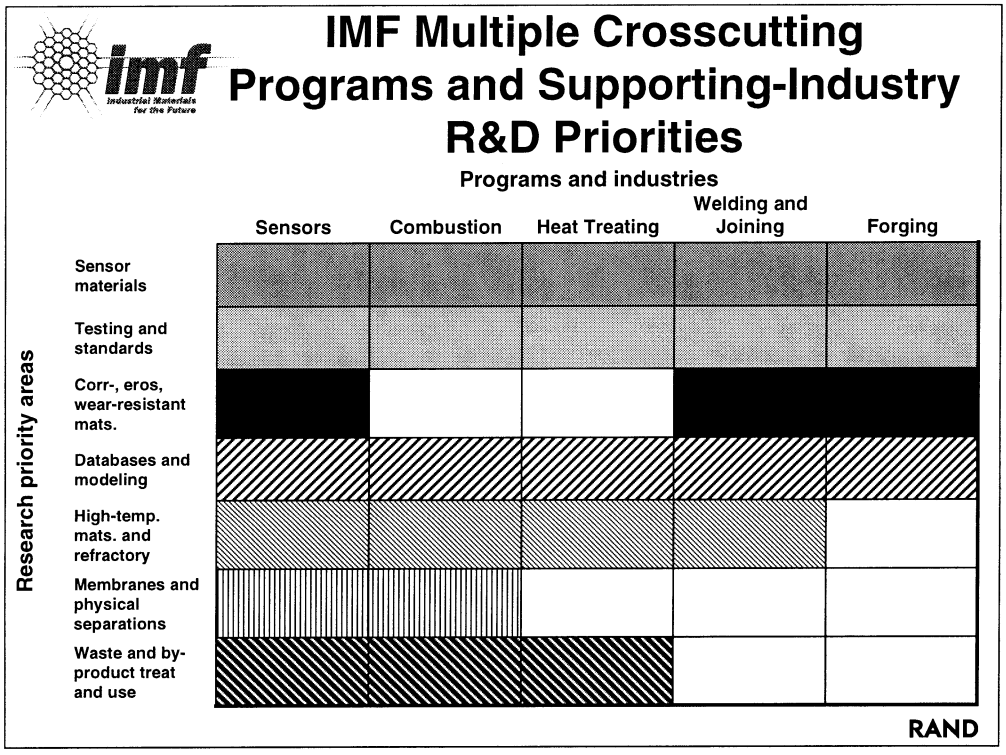
New materials for sensors are needed for NDE and process control for heat treating, forging, welding and joining, and combustion systems. Standards and testing are also required to define baseline properties and performance, measures of product quality, and methods for sampling, control, and optimization in all of these industries.

High-temperature materials R&D, including refractories, is needed to improve productivity and extend process equipment life in heat treating and combustion, allow sensor materials to perform and survive in high-temperature environments, and enable cost-effective weldable materials that meet Industries of the Future performance requirements.

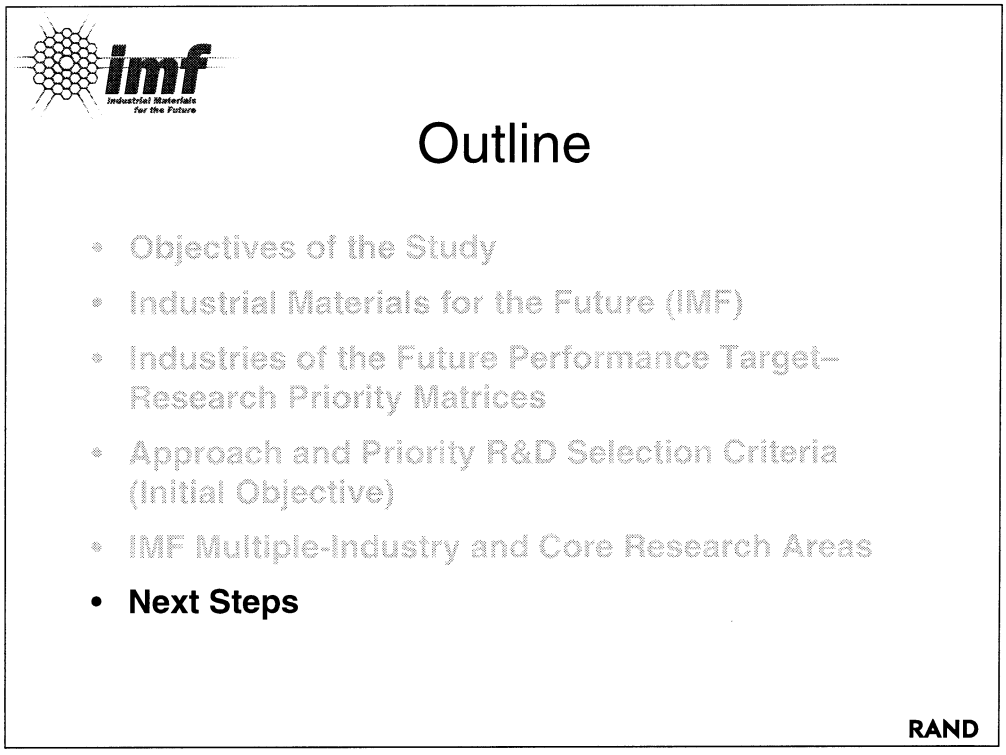
The waste and by-product treatment, recycling, and use area has high priority for used oil in heat treating; sensors for emission and effluent measurement; and simpler, more cost-effective processing of nitrogen oxides downstream of furnaces.

Corrosion-, erosion-, and wear-resistant materials are required to extend the lifetimes of sensors and forging dies. All five industries need materials that are also easy to weld and join without special preparation.

Membranes and physical separation methods are a high priority for sensors for mixed-materials sorting technology and for inexpensive separation of nitrogen from liquid fuels for combustion.



This slide summarizes the IMF research priorities for multiple crosscutting programs and supporting industries from the previous slides. The research-priority areas are shown as rows and the crosscutting programs and supporting industries as columns. Sensor materials, testing and standards, and databases and modeling apply to all five of the crosscutting programs and supporting industries. Joining and welding, coatings, and casting of tools and dies, which no more than one crosscutting program or supporting industry identified as a priority, do not appear on this slide.



This documented briefing described the results of the first task of this R&D identification and prioritization project, the identification of materials research needs of the Industries of the Future consistent with the mission of the IMF program. The next slide describes the next steps in continuing the project.

RAND will continue work on this project by describing materials performance goals for the multiple-industry R&D areas that emerged from the analysis of this documented briefing. The next step after that will be to describe the technical challenges—which in many cases will require core research efforts—as well as the benefits, of achieving these performance goals.

The final step in the project will be to prioritize the IMF research activities, emphasizing those that fill the gaps between (1) the basic research efforts of DOE's Office of Science and other organizations and (2) the industry-specific research efforts of the OIT industry teams.